Working memory capacity is equally unrelated to auditory distraction by changing-state and deviant sounds

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Abstract

The duplex-mechanism account states that there are two fundamentally different types of auditory distraction. The disruption by a sequence of changing auditory distractors (the changing-state effect) is attributed to the obligatory processing of the to-be-ignored information, which automatically interferes with short-term memory. The disruption by a sequence with a single deviant auditory distractor (the deviation effect), in contrast, is attributed to attentional capture. This account predicts that working memory capacity (WMC) is differentially related to the changing-state effect and to the deviation effect: The changing-state effect is assumed to be immune to cognitive control and, thus, to be unrelated to WMC. The deviation effect, in contrast, is assumed to be open to cognitive control and, thus, to be negatively related to WMC. Despite several methodological improvements over previous studies (large sample sizes, a composite measure of WMC, and a direct statistical comparison of the correlations), there was no evidence of a dissociation between the changing-state effect and the deviation effect. WMC was unrelated both to the size of the changing-state effect and to the size of the deviation effect, irrespective of whether simple stimuli (letters, Experiments 1 and 3) or complex stimuli (words and sentences, Experiment 2) were used as auditory distractors. Furthermore, a cross-experimental analysis with a total sample of $N = 601$ participants disconfirmed the idea that both types of auditory distraction show a differential relationship with WMC. Implications for models of auditory distraction are discussed.

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It is well established that task-irrelevant auditory stimuli disrupt working memory functions (Bell, Röer, & Buchner, 2013; Colle & Welsh, 1976; Ellermeier & Zimmer, 2014; Marsh, Röer, Bell, & Buchner, 2014; Schlittmeier, Hellbrück, & Klatte, 2008; Tremblay & Jones, 1998). Performance is impaired although participants are required to concentrate only on the visually presented stimuli, and are instructed to ignore all incoming auditory information. Although auditory information could, in principle, be efficiently suppressed at early stages of processing in cross-modal paradigms (Guerreiro, Murphy, & Van Gerven, 2010), there is often surprisingly substantial disruption of ongoing cognitive activities. This disruption can be seen as a failure of selective attention. Individuals with problems of controlling the contents of working memory may inadvertently process information that is irrelevant for the task at hand, which may interfere with the processing of the relevant material. However, involuntary attention switching has also been described as a vital built-in mechanism that is designed to monitor the environment for signals that are potentially relevant, and to interrupt ongoing processes once such stimuli are detected. According to the latter perspective, auditory distraction is the consequence of a system that has the delicate task of balancing out the conflicting goals of focusing on task-relevant information and remaining open for information that could be of even greater importance for the individual (e.g., the sound of a fire alarm during a written exam). In the present study, we examine the relationship between working memory capacity (WMC) and two commonly examined types of auditory distraction—distraction by changing-state sounds and distraction by deviant sounds—to gain a better understanding of the nature of these effects.

The standard paradigm for examining auditory distraction is the serial recall paradigm. A key finding in this paradigm is that the immediate serial recall of visually presented targets is impaired when auditory distractors are presented during target encoding or during a short retention interval (Buchner, Rothermund, Wentura, & Mehl, 2004; Miles, Jones, & Madden, 1991). The amount of distraction is mainly determined by the occurrence of abrupt changes in the to-be-ignored material and not by other potentially relevant variables such as sound level (Ellermeier & Hellbrück, 1998; Ellermeier & Zimmer, 2014). Two phenomena are often distinguished. First, the changing-state effect (Bell, Dentale, Buchner, & Mayr, 2010; Campbell, Beaman, & Berry, 2002; Jones & Macken, 1993; Jones, Madden, & Miles, 1992) refers to the observation that steady-state sequences consisting of repetitions of a single distractor item (e.g. AAAAAAAA) are less disruptive than changing-state sequences consisting of different distractor items (e.g. ABCDEFGH). Second, the deviation effect is caused by a violation of expectations that are based on regularities in the unfolding auditory stimulation (Hughes, Vachon, & Jones, 2007; Lange, 2005; Vachon, Labonté, & Marsh, 2017). Often, the deviation effect is examined by comparing steady-state sequences to deviation sequences with a single distractor item deviating from a repetitive sequence of steady-state distractors (e.g. AAAABAAA).

At first glance, the changing-state effect and the deviation effect seem to be quite similar in that both effects essentially show that abrupt changes in the auditory modality disrupt serial recall. Therefore, it seems reasonable to assume that both phenomena can be attributed to the same underlying mechanism. Such a unitary explanation is offered by the embedded-processes model (Cowan, 1995), which attributes both the changing-state effect and the deviation effect to attentional capture. The model assumes that incoming stimuli are automatically compared against a neural model of the previous stimulation. If a mismatch is detected, attention is involuntarily oriented towards this mismatch. The changing-state effect can be elegantly explained by this model by assuming that changes in the auditory modality lead to some degree of attentional orienting away from the rehearsal of the target material. Obviously, the explanation of the deviation effect does not require any additional assumptions within this model.

Despite their similarities, it has been proposed that the changing-state effect and the deviation effect require fundamentally different explanations. According to the duplex-mechanism account (Hughes, 2014; Hughes et al., 2007), the changing-state effect results from an automatic conflict between the obligatory processing of the order of the discrete distractor items and the voluntary processing of the order of the target items. More precisely, it is assumed that incoming distractor sequences are automatically segmented into auditory objects when differences between adjacent distractors are detected. The order of these auditory objects is preattentively processed, and this processing interferes with the maintenance of the order of the to-be remembered material. The repetition of a single distractor item does not yield any order information and therefore does not interfere with order maintenance. The deviation effect, in contrast, is attributed to a different mechanism: attentional capture. The violation of an expectation is assumed to capture attention, which interferes with the encoding—but not with the retention—of the target items (Hughes, Vachon, & Jones, 2005).

At first glance, it might seem surprising that two phenomena that are superficially so similar do require so fundamentally different explanations. Indeed, it has been acknowledged even by proponents of the duplex-mechanism account that, "on the face of it, the unitary account is the more attractive given its obvious parsimony" (Hughes et al., 2007, p. 1052), but they argue that the acceptance of the duplex-mechanism account is necessitated by dissociations between the changing-state effect and the deviation effect that cannot be easily integrated into a unitary account (Hughes, Hurlstone, Marsh, Vachon, & Jones, 2013; Hughes et al., 2005, 2007; Sörqvist, 2010; for a review see Hughes, 2014). In total, these empirical arguments are seen as so compelling that the duplex-mechanism account has become the standard model for understanding auditory distraction in recent years despite being less parsimonious than a unitary model (e.g. Elliott et al., 2016; Röer, Bell, & Buchner, 2013; Schwarz et al., 2015; Sörqvist, 2010).

Nevertheless, it has been argued that a closer look at the data reveals that the empirical basis is less compelling than often assumed (e.g. Röer, Bell, & Buchner, 2014a, 2015). A recurring problem is that the arguments in favor of a dissociation of the changing-state effect and the deviation effect more often than not rely on comparisons across different experimental setups that do not allow one to compare the two phenomena directly. This is not ideal for drawing conclusions because dissociations might have been produced by methodological differences between experiments rather than by differences between the changing-state effect and the deviation effect per se (see Röer et al., 2014a, for an example). These issues suggest that more direct evidence is necessary before concluding that "the distinction at the heart of the duplex-mechanism account" is necessitated by "various functional dissociations between the impact of an auditory deviation and the changing-state effect" (Hughes, 2014, p. 32).

Here, we focus on the assumption that inter-individual differences in working memory capacity (WMC) are negatively associated with the deviation effect while they are unrelated to the changing-state effect. This dissociation has been repeatedly brought forward in favor of functionally different mechanisms underlying these two effects (e.g., Hughes, 2014). The goal of the present study is to test this hypothesis, thereby overcoming some methodological problems that could have influenced the outcomes of previous studies on this issue.

Working memory is often thought to refer to a construct that provides quick access to information that is needed for ongoing cognitive processes (Wilhelm, Hildebrandt, & Oberauer, 2013). Accordingly, working memory capacity is thought to reflect inter-individual differences in the limited capacity of a person's working memory, that is, in the amount of information individuals have available for ongoing cognitive processes. Most tasks therefore require participants to store information over a short period of time while performing other cognitive activities such as solving arithmetic problems or reading sentences (Lewandowsky, Oberauer, Yang, & Ecker, 2010; Oswald, McAbee, Redick, & Hambrick, 2014; Redick et al., 2012). For example, in a typical complex-span task such as the operation span task (Turner & Engle, 1989), participants have to evaluate the correctness of mathematical equations, each followed by the presentation of a word. After having responded to a set of these equations, the participants are prompted to recall the presented words in their correct order.

There are different theoretical views on what underlies individual differences in WMC. For example, it has been suggested that inter-individual differences in WMC largely reflect the capacity with which memory processes such as rehearsal, maintenance, updating and controlled search can be carried out (Unsworth & Engle, 2007) or, alternatively, the efficiency with which short-term memory bindings (such as the binding of an item to its list position) can be formed and maintained (Wilhelm et al., 2013). According to the executive-attention view (Engle, 2002), WMC measures the individual ability to use cognitive control to focus attention on maintaining information in working memory while avoiding distraction by concurrent cognitive activities. This theoretical view is mainly based on findings showing that WMC predicts performance in tasks that require executive control such as the Stroop task or the dichotic-listening task (Conway, Cowan, & Bunting, 2001; Engle, 2002; Kane, Bleckley, Conway, & Engle, 2001), and is therefore often used in the irrelevant-sound literature to justify the prediction that persons with high WMC should be less distracted by attention-grabbing sound than persons with low WMC (Elliott & Cowan, 2005; Hughes, 2014; Hughes et al., 2013; Sörqvist, 2010). However, it is sensible to note that the view that high WMC is associated with a greater ability to resist interference is not unambiguously supported by the available literature (e.g. Friedman & Miyake, 2004; Oberauer, Lange, & Engle, 2004; Redick, Calvo, Gay, & Engle, 2011; Wilhelm et al., 2013). Furthermore, it seems obvious from the literature review presented above that the predictions of the relation between WMC and auditory distraction necessarily depend on the view of WMC that is adopted.

The embedded-processes model (Cowan, 1995) is usually interpreted as predicting that high WMC should be associated with a greater capacity to resist auditory distraction (Elliott, 2002; Elliott & Cowan, 2005; Hughes et al., 2013; Sörqvist, 2010; Sörqvist, Marsh, & Nöstl, 2013). Given that the model assumes that the changing-state effect and the deviation effect are both based on attentional capture, it seems reasonable to postulate that they should both be negatively correlated with WMC. This prediction is explicitly derived from the executive-attention view of WMC (Engle, 2002). However, other views of WMC lead to different predictions. Based on the view that individual differences in WMC reflect differences in mnemonic processing such as rehearsal (Unsworth & Engle, 2007), Elliot and Cowan (2005) entertained the possibility that WMC could even be *positively* related to the amount of distraction by irrelevant auditory distractors. Given that it is likely that auditory distraction interferes with the rehearsal of the target items (Röer, Bell, & Buchner, 2014b), distraction effects may be more pronounced in individuals with high WMC who show more rehearsal of the target items than individuals with low WMC because more rehearsal may provide more opportunity for disruption (Elliott & Cowan, 2005).

While it is not as easy as it may appear at first to derive a clear prediction from the embedded-processes model (Cowan, 1995) without making further assumptions about the nature of WMC, the model clearly *does not* predict that there should be any *differences* in the relationship between WMC and the changing-state effect on the one hand and WMC and the deviation effect on the other hand because both effects are attributed to the same process (attentional capture). Therefore, individual differences in WMC should be similarly related to both types of auditory distraction.

The duplex-mechanism account (Hughes, 2014; Hughes et al., 2013; Sörqvist, 2010), in contrast, predicts a differential relationship between WMC and the changing-state effect on the one hand and WMC and the deviation effect on the other hand. The key assumption of this account is that there is "a distinction between two forms of auditory distraction—one controllable by the individual, the other less so, if at all" (Hughes, 2014, p. 37f). One of the defining differences between the changing-state effect and the deviation effect is that the latter should be negatively related to WMC while the former should be unrelated to WMC (Hughes et al., 2013; Sörqvist, 2010). The changing-state effect is postulated to be immune to cognitive control because the effect is assumed to be underpinned by automatic, obligatory processing of order information that is not accessible to cognitive control, and does not involve attentional mechanisms. The processing of the order of the to-be-ignored distractors should be obligatory in individuals with high and low WMC. This leads to the prediction that the changing-state effect must be unrelated to WMC. Due to the greater involvement of attention, the deviation effect, in contrast, should be more open to top-down cognitive control than the changing-state effect. Individuals with high WMC should be better at voluntarily suppressing the bottom-up orientation of attention towards the deviant distractors than individuals with low WMC who should be more easily distracted (Hughes et al., 2013; Sörqvist, 2010). This leads to the prediction that the changing-state effect and the deviation effect should be differentially related to WMC. This is one of the dissociations that form the empirical basis of the duplex-mechanism account (Hughes, 2014).

In the past, the literature has often been presented as supporting the idea of a differential relationship of WMC to the changing-state effect and the deviation effect (Hughes, 2014). However, while it has been demonstrated repeatedly that distraction by changing-state sequences (consisting of letters, words, non-words, or tones) does not correlate with WMC (Beaman, 2004; Elliott & Briganti, 2012; Parmentier & Hebrero, 2013; Sörqvist, 2010; Sörqvist et al., 2013), the hypothesis of a negative relationship between the deviation effect and WMC can be challenged for several reasons. One reason is that previous studies yielded inconsistent results. While three experiments (Hughes et al., 2013; Sörqvist, 2010) showed that the deviation effect (operationalized as the difference between the steady-state and the deviation condition) was negatively correlated to performance in the operation span task, a later study with a primary focus on age differences in distraction failed to replicate this result: In this study, WMC was found to correlate neither with the changing-state effect nor with the deviation effect (Röer, Bell, Marsh, & Buchner, 2015) .

Another reason is that there are methodological issues as well that seem to necessitate further research. (1) The studies providing supporting evidence for a relationship between the deviation effect and WMC had only small to medium sample sizes (*N* = 24 in the experiment examining the deviation effect and *N* = 31 in the experiment examining the changing-state effect in the study of Hughes et al., 2013; *N* = 40 in Experiment 1 and *N* = 48 in Experiment 2 of Sörqvist, 2010), whereas the study that showed a null correlation had a sample size that was almost twice as large (*N* = 258) as the combined sample size of the other four studies. This is important because sample correlations are known to be variable and inaccurate in small samples and gradually stabilize at the level of the population correlation as the sample sizes increase (Schönbrodt & Perugini, 2013). Furthermore, studies with small samples often provide exaggerated estimates of effect sizes (Button et al., 2013). To avoid these problems, comparatively large samples were used in the present study. Obviously, a larger sample size should increase the statistical power to find a relationship between WMC and auditory distraction if it existed.

(2) In all previous studies only a single WMC measure was reported: performance in the operation span task. Specific WMC tasks such as the operation span task may measure task-specific variance that is unrelated to the construct of interest (Conway et al., 2005; Lewandowsky et al., 2010). For instance, the operation span task may reflect not only WMC, but also arithmetic capability. Therefore, it is often recommended to combine multiple measures (e.g., operation span and sentence span) into a composite WMC score to obtain a more general estimate of WMC with better psychometric properties (Conway et al., 2005; Wilhelm et al., 2013). In the present study, we used two different complex span tasks from a well-validated standardized working memory test battery with good psychometric properties (Lewandowsky et al., 2010). This approach should have further increased our chances to find a relationship between WMC and auditory distraction if it existed.

(3) Importantly, the hypothesis of a differential relationship of changing-state effect and deviation effect to WMC was not directly tested in previous studies although the main prediction of the duplex-mechanism account is that “there are fundamental differences between the changing-state effect and aspecific attentional

capture" (Hughes, 2014, p. 33). In the study of Hughes et al. (2013), changing-state effect and deviation effect were examined in different experiments, which makes a direct comparison of the correlations difficult. In the study of Sörqvist (2010), the conclusion that "the relationship between WMC and the deviation effect is significantly different from the relationship between WMC and the changing-state effect" (p. 657) was based on the finding that WMC correlated significantly with the deviation effect while the corresponding correlation between WMC and the changing-state effect did not attain significance. This interpretation is problematic because "the difference between 'significant' and 'not significant' is not itself statistically significant" (Gelman & Stern, 2006, p. 328). To illustrate, a data pattern where one correlation just reaches the statistical significance threshold (e.g., with $p = .04$) while the other just falls short of significance (e.g., with $p = .06$) does not provide conclusive evidence of a statistically significant dissociation. The relevant statistical test is whether the correlation between WMC and the deviation effect is significantly different from the correlation between WMC and the changing-state effect. This test was not reported. Without the relevant statistical test, it is difficult to draw clear conclusions from these studies (Diedenhofen & Musch, 2015; Nieuwenhuis, Forstmann, & Wagenmakers, 2011). In fact, the difference between the correlations observed by Hughes et al. (2013) would not have reached significance even when tested with a one-sided test, $z = 1.55$, $p = .06$.[1] This means that there is no clear"psychometric evidence for the dissociation between the two forms of auditory distraction" (Hughes et al., 2013, p. 549), but a *p*-value of .06 in combination with small sample sizes also does not provide clear evidence against it either. Given that the available evidence does not allow us to draw clear conclusions about this issue, there is need for further research in which this hypothesis is tested directly.

In the present study, we applied a statistical test of significance between correlations (between WMC and the changing-state effect on the one hand and WMC and the deviation effect on the other hand). This allowed us to directly test the central prediction of the duplex-mechanism account that there should be a dissociation between the changing-state effect and the deviation effect. More precisely, the duplex-mechanism account predicts that there is a negative relationship between WMC and the deviation effect while the relationship between WMC and changing-state distraction is absent. This leads to the statistical prediction that the correlation between WMC and the deviation effect should be significantly different from the correlation between WMC and the changing-state effect.

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[1] It is not possible to perform a significance test based on the results reported by Sörqvist (2010).

Experiment 1

Method

Participants

A total of 138 students at Heinrich Heine University Düsseldorf (95 women) with a mean age of 24 years (*SD* = 5) participated in exchange for course credit or a small honorarium. All participants were fluent German speakers and reported normal hearing and normal or corrected-to-normal vision.

Materials and Procedure

Working memory tasks. In order to minimize the task-specific variance associated with single complex span tasks (Conway et al., 2005; Lewandowsky et al., 2010), we applied two different complex span tasks: the operation span task and the sentence span task. These tasks were taken from the German version of the well-validated computerized working memory test battery for the Psytoolbox in MATLAB by Lewandowsky et al. (2010) available at http://www.psychologie.uzh.ch/fachrichtungen/allgpsy/Software.html. Given that the WMC tasks are described in full detail in Lewandowsky et al. (2010), only the key features of the tasks are described here.

In each trial of the operation span task, participants were shown a simple mathematical equation (e.g. 5 - 2 = 3) and had to evaluate its correctness by pressing keys labeled with "correct" or "incorrect" on the computer keyboard. After the participants' response, the equation disappeared and was replaced by a consonant that had to be memorized. The number of alternating equations and thereby the list length of the to-be-remembered consonants reached from four to eight. There were three trials of each list length, resulting in a total number of 15 trials. Additionally, three training trials with list lengths of three, four and five preceded the experimental trials. The letter sequence, equations, and trial order were presented in the same random order for all participants.

The sentence span task differed from the operation span task only in that arithmetic equations were replaced by sentences (e.g. the German translation of "all men wear beards"), the meaningfulness of which had to be judged. The list length of to-be-remembered consonants reached from three to seven and the training trials comprised three trials with list lengths of two, three and four.

Serial recall. A standard serial recall task was used with visual to-be-remembered sequences that consisted of eight digits sampled randomly without replacement from the set {1,2,…, 9}. The digits were presented successively (700 ms on, 300 ms off) in a 72-point equidistant black Monaco font on a white background in the center of a 21.5-inch computer screen. Participants were seated approximately 45 cm from the screen, hence the visual angle of the digits subtended 1.49° vertically and 0.92° horizontally.

As in Sörqvist (2010), auditory distractor sequences consisted of to-be-ignored letters. The letters B, F, G, H, J, L, M, Q, R, S, T, V, Z were recorded at 44.1 kHz, using 16-bit encoding in a monotone male voice. They were normalized to minimize amplitude differences among the stimuli and had an average sound level of 60 dB(A) L_{eq}. Using these stimuli, three types of distractor conditions were generated.

In the steady-state condition, a randomly chosen letter was repeated 18 times with a rate of 500 ms (e.g., B B B B B B B B B B B B B B B B B B). For each participant, one steady-state sequence was created and used in all steady-state trials within the experiment. The deviation sequences were identical to the steady-state sequences with the exception that the ninth letter of each sequence was replaced by another letter (e.g., B B B B B B B B *Q* B B B B B B B B B). The deviant letter was randomly drawn from the distractor set with the constraint that each letter was only used twice as a deviant within the experiment. Note that we used a verbal deviant as in Experiment 1 of Sörqvist (2010) rather than a tone or voice deviant (as in Experiment 2 of Sörqvist and Experiment 3b of Hughes et al.) because we expected (based on pilot studies) that this manipulation would result in comparatively large distraction effects. For the changing-state sequences, nine letters were randomly drawn from the letter set and presented twice. The order of the letters was random with the constraint that successive distractors were not the same letters (e.g., J R Z V T J V M S G M F R T S Z G F).

Each serial recall trial started with the consecutive presentation of the eight to-be-remembered digits. Within the experimental trials, the onset of the first distractor letter preceded the onset of the first to-be-remembered digit by 300 ms and the final spoken letter was presented 500 ms after the offset of the last to-be-remembered digit. Using these timing parameters, the deviant letter in the deviation condition occurred 300 ms before the fifth to-be-remembered digit (similar to the study of Sörqvist, 2010). Eight question marks appeared at the computer screen 500 ms after the final spoken letter had been presented. Participants were required to recall the to-be-remembered digits in the order in which they had been presented. The digits were typed into the computer keyboard, which replaced the question marks on the screen. Correcting answers was not possible, but participants could indicate that they did not remember a certain digit by pressing a “don’t know” button. After all responses were given, the next trial was initiated when the participants pressed the space bar.

After two quiet training trials, which served to familiarize the participants with the task, 96 experimental trials were completed. As in previous studies (Sörqvist, 2010), the experimental trials were divided into a changing-state block and a deviation block, which were separated by a self-paced pause. The changing-state block consisted of 24 steady-state and 24 changing-state trials, and the deviation block consisted of 24 steady-state and 24 deviation trials. The order of trials within the blocks was randomized, and the order of the blocks was counterbalanced across participants. The experimental session lasted approximately 60 minutes.

All participants started with the operation span task followed by the sentence span task and the serial recall task. For all tasks, written instructions were given on the computer screen. Before starting with the WMC tasks, participants were instructed to work as accurately and as quickly as possible. Before starting the serial recall task, participants were informed that they should ignore any sound they might hear through their headphones and that they should not pronounce any to-be-remembered digits.

Power analysis

Given a total sample size of $N = 138$ and $\alpha = .05$, it was possible to detect a correlation of $\rho = -.40$ (between changing-state or deviation distraction and WMC) with a statistical power of $1 - \beta > .99$ in a one-sided test. The power calculations were conducted using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007).

Results

WMC measures

As suggested by Conway et al. (2005), a partial-credit load scoring was used for the WMC tasks: For each list length, the proportion of items recalled in the correct serial position was calculated, and these proportions were averaged to obtain the operation span and sentence span scores (see also Lewandowsky et al., 2010). The descriptive data of the WMC tasks are reported in Table 1. As expected (Lewandowsky et al., 2010; Redick et al., 2012), participants who scored high in the operation span task also scored high in the sentence span task, $r = .60$, $p < .001$, suggesting that both tasks measure the same underlying construct. The operation span score and sentence span score were averaged to obtain a composite WMC score with better psychometric properties. This WMC score was used in all subsequent statistical analyses (for the descriptive results, see Table 1).

Serial Recall

As in previous studies, a strict serial recall criterion was used to analyze serial recall performance. The serial recall score represents the proportion of digits that were recalled in the same serial position in which they had been presented. Repeated-measures MANOVAs confirmed that serial recall was disrupted by changing-state distractor sequences compared to the steady-state distractor sequences in the changing-state block, $F(1,137) = 144.76$, $p < .001$, $\eta_p^2 = .51$, and by the deviation distractor sequences compared to the steady-state distractor sequences in the deviation block, $F(1,137) = 13.18$, $p < .001$, $\eta_p^2 = .09$ (see Figure 1). Following the usual procedure (e.g. Hughes et al., 2013; Röer, Bell, Marsh, et al., 2015; Sörqvist, 2010), individual differences in distraction were measured by calculating the difference between the serial recall scores in the changing-state or deviation conditions and the corresponding steady-state control conditions. Note that difference measures representing the changing-state effect (*M* = .09, *SD* = .09) and the deviation effect (*M* = .02, *SD* = .07) correlated significantly with each other, *r* = .28, *p* < .01. This could arguably point to the fact that both measures may reflect, in part, the same construct.

We also conducted reliability analysis for our differences scores, following the procedure of Elliot and Cowan (2005). Based on the raw measures, proportion correct scores from adjacent trials were used to create steady-state – changing-state and steady-state – deviant difference scores for each participant, resulting in 24 difference scores for every participant, which were used to calculate Cronbach's alpha. We obtained Cronbach's alphas of α = .62 for the changing-state effect and α = .30 for the deviation effect.[2]

Relationship between WMC and auditory distraction

As in previous studies (Ellermeier & Zimmer, 1997; Hughes et al., 2013; Sörqvist, 2010), correlation analyses were conducted to measure the relationship of WMC with

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[2] Note that these are typical values for difference measures, which are comparable with those obtained with changing-state distractors in previous studies (Ellermeier & Zimmer, 1997; Elliott, Barrilleaux, & Cowan, 2006; Elliott & Cowan, 2005). Compared to the changing-state effect, the deviation effect is typically much smaller (e.g., Hughes et al., 2013; Hughes et al., 2005; Röer, Bell, Marsh, et al., 2015; Sörqvist, 2010), so that an even lower reliability is to be expected; however, unfortunately, there is no previous study that reported the reliability of the deviation effect.

the changing-state and the deviation effect. Given the directional hypothesis (WMC was hypothesized to be negatively correlated with auditory distraction), only one-sided tests are reported. As expected, the correlation between the composite WMC score and the changing-state effect was not significant, $r = .04$, $p = .67$ (see upper panel of Figure 2), but WMC did not correlate significantly with the deviation effect either, $r = - .01$, $p = .45$ (see lower panel of Figure 2).[3]

To evaluate the duplex-mechanism account's central prediction of a dissociation between the changing-state effect and the deviation effect, it is necessary to compare the two correlations directly (Diedenhofen & Musch, 2015; Nieuwenhuis et al., 2011). It seemed most appropriate to use a one-sided test to evaluate the directional hypothesis that the relationship between WMC and the deviation effect should be more negative than the relationship between WMC and the changing-state effect. Given that the two correlations are dependent (comparison within the same group) and overlapping (the same variable, WMC, is part of both correlations), we used the Williams *t* test statistic (Williams, 1959), as recommended by Hittner, May and Silver (2003) as well as Steiger (1980) to test whether the correlation between WMC and the changing-state effect and the correlation between WMC and the deviation effect are significantly different from each other. The comparison of the correlations was computed using the free software

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[3] Correlating the changing-state effect and the deviation effect with the operation span score and the sentence span score separately did not yield different conclusions.

package *cocor* (Diedenhofen & Musch, 2015; available at http:// comparingcorrelations.org). The analysis showed that the correlation between WMC and the changing-state effect did not differ significantly from the correlation between WMC and the deviation effect, *Williams' t*(135) = 0.48, *p* = .32.

To further substantiate the null findings, we carried out a supplementary (directional) Bayesian analysis of the results using the free computer software JASP (available at https://jasp-stats.org), using a default Cauchy prior width of 1 (Wagenmakers, Verhagen, & Ly, 2016). The Bayes factor was $BF_{01} = 12.96$ for the correlation of WMC with the changing-state effect and $BF_{01} = 8.50$ for the correlation of WMC with the deviation effect, which indicates that the observed data are 12.96 times (changing-state effect) and 8.50 times (deviation effect) more likely under the null hypothesis than under the alternative hypothesis. Given that Bayes factors between 3-10 are commonly interpreted as substantial evidence in favor of the null hypothesis and Bayes factors of > 10 count as strong evidence in favor of the null hypothesis (Wetzels & Wagenmakers, 2012), these analyses further support the conclusions that WMC is unrelated to both the changing-state effect and the deviation effect.

In the present study, we followed the examples of Hughes et al. (2013) and Sörqvist (2010) by subtracting performance in the changing-state and the deviation condition from the corresponding steady-state control condition and correlated the resulting difference measures with WMC. However, the use of difference measures in correlations can be problematic due to uncorrelated error terms in the raw scores, which makes them less reliable (Cronbach & Furby, 1970; Ellermeier & Zimmer, 1997; Elliott et al., 2006; Elliott & Cowan, 2005). As pointed out by Ellermeier and Zimmer (1997), this problem should be even more pronounced when the difference scores are based on a small number of trials, which applies to the studies of Sörqvist (2010) and Hughes et al. (2013) with only six changing-state and six deviation trials, respectively. To alleviate this problem, previous studies (Elliott et al., 2006; Elliott & Cowan, 2005; Sörqvist, 2010; Sörqvist, Nöstl, & Halin, 2012) reported supplementary hierarchical regression analyses to determine the additional amount of variance explained by WMC in the changing-state or deviation condition after having entered performance in the steady-state control condition in the model as a predictor (Cronbach & Furby, 1970). Performance scores in the changing-state or the deviation condition were used as the dependent variables, performance in the corresponding steady-state conditions were entered as independent variables in the first step (to remove variance due to the baseline measure), and WMC scores were entered in the second step (cf. Sörqvist, 2010; Sörqvist et al., 2012). Following these examples we report supplementary regression analyses of the data. The first regression analysis showed that a significant part of the variance in the changing-state performance was explained by the corresponding steady-state performance ($R^2 = .$

65, $F[1,136] = 253.74$, $p < .001$). However, entering the WMC score in the second step did not lead to a significant increase in the amount of explained variance ($\Delta R^2 < .01$, $\Delta F[1,135] = .20$, $p = .65$). In other words, the WMC score was not significantly related to the variance in the changing-state performance that was not already explained by the steady-state performance. The same results were obtained for the deviation effect. A significant part of the variance in the deviation performance was explained by the corresponding steady-state performance ($R^2 = .78$, $F[1,136] = 485.02$, $p < .001$). Entering the WMC score in the second step did not lead to a significant increase in the amount of explained variance ($\Delta R^2 < .01$, $\Delta F[1,135] = 1.88$, $p = .17$), showing that the WMC score was not significantly related to the variance in the deviation performance that was not already explained by the steady-state performance. The reliability of the regression residuals were analyzed following the procedure for difference measures by Elliot and Cowan (2005) explained above. As was to be expected for theoretical reasons (Cronbach & Furby, 1970), the Cronbach's alphas of the residuals representing the changing-state and the deviation effect were indeed higher ($\alpha = .86$ for the changing-state effect and $\alpha = .82$ for the deviation effect) than the reliabilities of the differences measures (reported in the *Serial Recall* section above). Nevertheless, both analyses disconfirmed the hypothesis of a significant relationship between WMC and the distraction by auditory deviants.

Discussion

The results of Experiment 1 confirm previous reports that WMC is unrelated to the changing-state effect (Hughes et al., 2013; Röer, Bell, Marsh, et al., 2015; Sörqvist, 2010; Sörqvist et al., 2013). This is not surprising insofar as there is a broad consensus about this null correlation. A more controversial issue is whether or not there is a negative relationship between WMC and the deviation effect. Experiment 1 disconfirmed this hypothesis although a large sample size, a composite WMC score, one-sided tests as well as additional regression analyses were used. All of these factors should have increased the probability of finding a significant relationship between WMC and the deviation effect if it existed. A comparison between the correlations directly disconfirmed the central prediction of the duplex-mechanism account (Hughes, 2014) that changing-state effect and deviation effect are differentially related to WMC.

Given the heterogenous pattern of results in previous studies, we aimed at replicating the results of Experiment 1 in a second experiment. We also wanted to address a potential concern about Experiment 1. The present Experiment 1 was similar to Experiment 1 reported by Sörqvist (2010) in that consonants were used as auditory distractors, the deviation was a change in stimulus identity, and the deviant distractor occurred shortly before the onset of the fifth to-be-remembered digit. The main difference was that the deviation sequences were presented in half of the trials of the deviation block in Experiment 1. This is in contrast to most previous studies in which the auditory deviations were only presented in a small number of trials (six out of 28 trials in the study of Sörqvist, 2010, and six out of 46 trials in the study of Hughes et al., 2013). Given that the deviation effect is assumed to be caused by expectancy violations (Nöstl, Marsh, & Sörqvist, 2012, 2014; Röer et al., 2013; 2014b; Vachon, Hughes, & Jones 2012), it seems conceivable that the comparatively large number of deviation trials may have influenced the results. If people are more disrupted by rare deviations, the larger deviation effects could increase the chances of finding significant correlations with WMC. Given that no solid knowledge seems to be available about the effect of the proportion of deviation trials within the serial recall paradigm, one aim of Experiment 2 was to test whether or not a small proportion of deviation trials would lead to a larger deviation effect than an equal proportion of deviation and control trials.

We also used more complex distractor material in Experiment 2 than in Experiment 1 (sentences and words instead of consonants). Compared to letters, sentences and words contain more changes in rhythm and frequency, which may increase the magnitude of auditory distraction (Ellermeier & Zimmer, 2014; Jones & Macken, 1993; Schlittmeier, Weisgerber, Kerber, Fastl, & Hellbrück, 2012), and, thereby, the likelihood that these effects can be modulated by cognitive control (Röer, Bell, & Buchner, 2015). Another difference to Experiment 1 was that participants completed the changing-state block and the deviation block on two separate days. The span tasks were administered on both days, and combined into a single general WMC score. These changes were made to further increase the chances of finding significant correlations between WMC and auditory distraction if such relationships existed.

Experiment 2

Method

Participants

Sixty-three students at Heinrich Heine University Düsseldorf (42 women) with a mean age of 25 years (*SD* = 5.99) participated in exchange for course credit or a small honorarium. All were fluent German speakers and reported normal hearing and normal or corrected-to-normal vision.

Materials and Procedure

Materials and procedure were identical to those of Experiment 1 with the following exceptions. The changing-state sequences consisted of 24 German sentences (as in the studies of Bell, Röer, Dentale, & Buchner, 2012; and of Röer, Bell, & Buchner, 2015). The sentences (e.g., “Peel and quarter the onions, and slice them into thin pieces, then add the tomatoes, then simmer it at medium heat.”) were spoken by a male voice and lasted nine seconds, parallel to the sequences in Experiment 1. All steady-state sequences consisted of 18 repetitions of the same monosyllabic word that was randomly drawn from a pool of 25 words sampled from the sentences (e.g., "then, then, then, then, then, then, then, then, then, then, then, then, then, then, then, then, then, then"). The deviation sequences were identical to the steady-state sequences with the exception that the ninth word of each sequence was replaced by a monosyllabic deviant word (e.g., "then, then, then, then, then, then, then, then, *world*, then, then, then, then, then, then, then, then, then") that differed from trial to trial.

In contrast to Experiment 1, participants completed the changing-state block and the deviation block on two different days. On each day, participants completed both the operation span task and the sentence span task so that the span scores of each session could be combined to further enhance the psychometric properties of the WMC measure, and to assess the stability of the WMC scores.

The proportion of changing-state trials and deviation trials within each block was manipulated between subjects. Participants were assigned to one of two groups on an alternating basis (i.e., Participant 1 was assigned to Group 1, Participant 2 was assigned to Group 2, Participant 3 was assigned to Group 1, and so on). In one group, the changing-state trials and deviation trials were as frequent as the steady-state trials: Participants completed 24 changing-state trials and 24 steady-state trials in the changing-state block and 24 deviation trials and 24 steady-state trials in the deviation block (as in Experiment 1). The order of trials was randomized. In the other group, the changing-state trials and deviation trials were rare in comparison to the steady-state trials (as in the studies of Hughes et al., 2013, and Sörqvist, 2010): Participants completed eight changing-state trials and 40 steady-state trials in the changing-state block, and eight deviation trials and 40 steady-state trials in the deviation block. To ensure that the eight changing-state trials were distributed evenly across the whole block of 48 trials, the order of the trials was randomly determined with the restriction that half of the changing-state trials were presented in the first half of the block, and the other half of the changing-state trials were presented in the second half of the block. The same was true for the deviation trials in the deviation block.

The order of the changing-state block and the deviation block, as well as the order of the working memory tasks and serial recall task within each session, were counterbalanced across participants. Each experimental session lasted approximately 40 minutes.

Power analysis

Given a total sample size of $N = 63$ and $\alpha = .05$, it was possible to detect a correlation of $\rho = –.40$ (between changing-state or deviation distraction and WMC) with a statistical power of $1 – \beta = .95$ in a one-sided test.

Results

WMC measures

The WMC measures were scored the same way as in Experiment 1. The individual scores of the two sessions were correlated to obtain test-retest reliabilities. The test-retest reliabilities were $r = .71$ for the operation span task and $r = .66$ for the sentence span task, consistent with previous reports (Redick et al., 2012). For each participant, a single operation span score and a single sentence span score were obtained by averaging across the scores from both days. Participants who scored high in the operation span task also scored high in the sentence span task, $r = .76$, $p < .001$. Therefore, it seemed justified to combine both scores into a single WMC score, as in Experiment 1. This composite WMC score serves as the basis for the following analyses (for the descriptive results, see Table 1).

Serial recall

Repeated-measures MANOVAs confirmed that serial recall was disrupted by the changing-state distractor sequences compared to the steady-state distractor sequences in the changing-state block, $F(1,61) = 99.08$, $p < .001$, $\eta_p^2 = .62$, and by the deviation distractor sequences compared to the steady-state distractor sequences in the deviation block, $F(1,61) = 22.68$, $p < .001$, $\eta_p^2 = .27$ (see Figure 3). Frequency of the changing-state or deviation distractors had no main effect on performance in the changing-state block,

$F(1,61) = 0.24$, $p = .63$, $\eta_p^2 < .01$, or in the deviation block, $F(1,61) = 1{,}50$, $p = .23$, $\eta_p^2 = .02$, respectively. Even more importantly, frequency did not modulate either the changing-state effect, $F(1,61) = 0.08$, $p = .77$, $\eta_p^2 < .01$, or the deviation effect, $F(1,61) = 0.17$, $p = .68$, $\eta_p^2 < .01$.

Difference scores representing the changing-state effect and the deviation effect were calculated as in Experiment 1. The changing-state effect ($M = .12$, $SD = .10$) and the deviation effect ($M = .04$, $SD = .07$) did not correlate significantly, $r = .09$, $p = .49$, when calculated across both frequency conditions. However, when this correlation was calculated for the frequency conditions separately, there was a significant correlation between the changing-state effect ($M = .13$, $SD = .09$) and the deviation effect ($M = .04$, $SD = .06$) in the condition with the balanced amount of trials in every condition in each block $r = .29$, $p = .05$. In the condition in which only eight changing-state or deviant trials were compared to 40 steady-state trials, the correlation between the changing-state effect ($M = .12$, $SD = .10$) and the deviation effect ($M = .05$, $SD = .08$) did not correlate significantly $r = -.06$, $p = .37$, which can be attributed to the low reliability of the difference scores in this condition (see below).

For the condition with an equal amount of trials in each condition per block, the reliability was calculated as in Experiment 1, following the procedure of Elliot and Cowan (2005). In this condition Cronbach's alpha was $\alpha = .56$ for the changing-state effect and $\alpha = .12$ for the deviation effect. In the condition with only eight changing-state and eight deviation trials that were compared to 40 steady-state trials, we first averaged the proportion correct scores for each set of 5 adjacent steady-state trials (e.g. steady-state trial 1 to 5, 6 to 10, 11 to 15 etc. were averaged) separately for each block. Subsequently, the corresponding changing-state and deviant trials were subtracted from these values (e.g. trial 1 in the changing-state condition was subtracted from the averaged steady-state score from trial 1-5 in the changing-state block), which resulted in eight difference scores for the changing-state effect and eight difference scores for the deviation effect, which were then used to calculate Cronbach's alpha. In this condition Cronbach's alpha was $\alpha = .37$ for the changing-state effect and $\alpha < .01$ for the deviation effect. This confirms that reliabilities are poor when difference scores are based on only a small number of changing-state and deviation trials (see Ellermeier & Zimmer, 1997).

Relationship between WMC and auditory distraction

Given that frequency did not affect distraction, this variable was not further considered in the analyses of the relationship between WMC and auditory distraction[4]. As in Experiment 1, there was no significant correlation between WMC and the changing-state effect, $r = -.11$, $p = .21$ (see upper panel of Figure 4). Likewise, no significant correlation was found between WMC and the deviation effect, $r = -\ .03$, $p = .$

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[4] The conclusions, however, do not change when the frequent and the rare condition are considered separately.

42 (see lower panel of Figure 4)[5]. The descriptive tendency is towards a somewhat stronger negative relationship between WMC and the changing-state effect in comparison to that between WMC and the deviation effect, which is the opposite of what the duplex-mechanism account predicts. For the sake of completeness, a direct comparison between the correlation of WMC with the changing-state effect on the one hand and between WMC with the deviation effect on the other hand yielded a non-significant result, *Williams' t*(60) = - 0.46, *p* = .67.

A supplementary (directional) Bayesian analysis yielded Bayes factors of BF_{01} = 2.89 for the correlation between WMC and the changing-state effect and BF_{01} = 5.34 for the correlation between WMC and the deviation effect, which indicates that the observed data are 2.89 times (changing-state effect) and 5.34 times (deviation effect) more likely under the null hypothesis than under the alternative hypothesis.

As in Experiment 1, and following other researchers in the field (Sörqvist, 2010; Sörqvist et al., 2012), regression analyses were performed in which changing-state performance was used as the dependent variable and performance in the corresponding steady-state condition and the WMC score were used as independent variables. Again, a significant part of the variance in the changing-state performance was explained by the corresponding steady-state performance (R^2 = .53, *F*[1,61] = 68.08, *p* < .001), but

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[5] Correlating the changing-state effect and the deviation effect with the operation span score and the sentence span score separately would have led to identical conclusions.

entering the WMC score in the second step did not lead to a significant increase in the amount of explained variance ($\Delta R^2 = .02$, $\Delta F[1,60] = 2.02$, $p = .16$), showing that the WMC scores were not significantly related to the variance in the changing-state performance that was not already explained by the steady-state performance. Also parallel to the results of Experiment 1, a significant part of the variance in the deviation performance was explained by the corresponding steady-state performance ($R^2 = .78$, $F[1,61] = 213.23$, $p < .001$), but entering the WMC score in the second step did not lead to a significant increase in the amount of explained variance ($\Delta R^2 < .01$, $\Delta F[1,60] = .26$, $p = .61$), showing that the WMC score was not significantly related to the variance in the deviation performance that was not already explained by the steady-state performance.

We again estimated the reliability of the regression residuals, following the same procedure used when analyzing the raw difference scores described above. In the frequent condition, Cronbach's alpha of the residuals was $\alpha = .85$ for the changing-state effect and $\alpha = .80$ for the deviation effect. In the rare condition, Cronbach's alpha of the residuals was $\alpha = .45$ for the changing-state effect and $\alpha = .29$ for the deviation effect. This again confirms that reliabilities are poorer when they are based on only a small number of changing-state and deviation trials (see Ellermeier & Zimmer, 1997).

Discussion

The first interesting finding of Experiment 2 is that the frequency of the changing-state or deviation sequences within each block did not modulate auditory distraction at all. Therefore, it is possible to conclude that our decision to present a larger number of deviation trials in Experiment 1 does not seem to be responsible for the differences between the present results and those of Sörqvist (2010) because increasing the number of trials did not affect the deviation effect at all. However, reducing the number of changing-state or deviation sequences within each block decreases the reliability of our difference measures and regression residuals and thus reduces the chance of finding a relationship between WMC and auditory distraction if it existed. A priori, it was not clear whether or not the size of auditory distraction may be modulated by the proportion of deviation trials within a block. While it has been shown that a deviation from a regular pattern across trials can significantly affect performance (Röer, Bell, Dentale, & Buchner, 2011; Vachon et al., 2012), other results suggest that the immediately preceding information (within a trial) is most potent in determining attentional capture (Röer et al., 2014b). The present results revealed that neither the deviation effect nor the changing-state effect were significantly affected by the frequency of deviation or changing-state trials within a block, supporting the latter notion that disruption is mainly determined by the changes within a trial, and less so by changes across trials (Röer et al., 2014b). This conclusion is also consistent with previous findings showing that there is only minor stimulus-unspecific habituation across the trials of the experiment when the auditory material is unattended (Hughes et al., 2005; Röer et al., 2011).

The finding of Experiment 1 that WMC was unrelated to both the changing-state effect and the deviation effect was replicated. Importantly, the correlation between WMC and changing-state effect did not differ significantly from the correlation between WMC and the deviation effect in Experiment 2 , just like in Experiment 1. The descriptive tendency was even in the opposite direction of what the duplex-mechanism account predicts. The results of Experiment 2 therefore provide further evidence against a dissociation between the changing-state effect and the deviation effect.

A reviewer of a previous version of this article pointed out that Experiments 1 and 2 do not provide a close replication of the previous studies that have reported significant correlations between WMC and the deviation effect (Hughes et al., 2013; Sörqvist, 2010). This might be considered problematic because the effect size of the deviation effect in Experiment 1 of Sörqvist (2010) was much larger (η_p^2 = .55) than the deviation effects obtained in the present study. Given that the effect sizes obtained here are more similar to those obtained in other studies (e.g., Hughes et al., 2005, 2007), it seems possible that the effect reported by Sörqvist—that was based on a comparatively small sample—simply represents an overestimation of the effect. It is, however, also possible that—due to several methodological deviations from the original studies—the first two experiments reported here provide less ideal conditions to detect a relationship between WMC and the deviation effect than Experiment 1 of Sörqvist (2010) because they provide less optimal conditions to produce exceptionally large attentional capture effects. The only way to test this possibility properly is to perform a close replication of Experiment 1 of Sörqvist (2010). Therefore, we conducted a third experiment in which we aimed at replicating Experiment 1 of Sörqvist (2010) as closely as possible.

Experiment 3

Method

Participants

One hundred and forty-two students at Heinrich Heine University Düsseldorf (110 women) with a mean age of 22 years (*SD* = 3.69) participated in exchange for course credit or a small honorarium. All were fluent German speakers and reported normal hearing and normal or corrected-to-normal vision.

Materials and Procedure

Given that Experiment 3 was a close replication of Experiment 1 of Sörqvist (2010) only the key aspects of this experiment are described here. All participants started with the working memory task, followed by the serial recall task.

Working memory task. To measure individual WMC, an adapted version of the operation span task (Turner & Engle, 1989) was used, in which participants had to evaluate the correctness of mathematical equations by pressing keys labeled with "yes" and "no". After that, one-syllable nouns had to be memorized. List length of the to-be-remembered nouns ranged from two to six. There were three trials of each list length, resulting in a total number of 15 experimental trials.

Serial recall. The visual to-be-remembered sequences consisted of eight digits sampled randomly without replacement from the set {1,2,…, 9}. The digits were presented successively for 350 ms with an inter-stimulus interval of 400 ms in a pseudorandom order, in which the successive digit were not allowed to be arithmetically adjacent. The distractor sequences consisted of the four letters c, k, m, j, spoken by a male voice and edited to last 200 ms. In the steady-state condition, the letter "c" was repeated 21 times, separated by a 100 ms inter-stimulus interval. The deviation condition was identical to the steady-state condition with the exception that the 11th spoken "c" was replaced by the letter "k". The changing-state condition was identical to the other conditions, except that all four letters (c, k, m, j) were repeatedly presented in the same order.

Changing-state and deviation trials were presented in separate blocks. Each block comprised 30 trials. The changing-state block consisted of 24 steady-state and six changing-state trials, occurring at ordinal trial numbers 5, 9, 15, 21, 24, and 29. The deviation block was identical to the changing-state block, except that six deviant sequences were presented instead of six changing-state sequences. The order of the two blocks was counterbalanced across participants.

The main difference between the present Experiment 3 and Experiment 1 of Sörqvist (2010) was that after the completion of the first two serial recall blocks, we presented both blocks a second time (in the same order). This change in procedure aimed at increasing the reliability of the dependent measures by aggregating over more (twice as many) trials (Ellermeier & Zimmer, 1997). Given that these blocks were presented after the replication of Experiment 1 of Sörqvist (2010) was completed, it is possible to perform two different analyses with these data: (1) a direct replication of Experiment 1 of Sörqvist (2010), in which only the first two blocks are considered, and (2) a complete analysis of all four blocks, which may have the advantage of better psychometric properties of the measures. To anticipate, reliabilities of the distraction effects were indeed better when performance was aggregated over a greater number of trials, but the statistical conclusions did not change as a function of whether only the first two or all four blocks were analyzed. In the Results section, we will report the data of the entire experiment, but we will return to this issue in the Discussion.

Power analysis

Given a total sample size of $N = 142$ and $\alpha = .05$, it was possible to detect a correlation of $\rho = - .40$ (between changing-state or deviation distraction and WMC) with a statistical power of $1 - \beta > .99$ in a one-sided test.

Results

WMC measure

The operation span scores (see Table 1) were calculated the same way as in Sörqvist (2010) and the present Experiments 1 and 2.

Serial recall

Consistent with the analysis reported by Sörqvist (2010), the first two steady-state trials in each block were excluded from the analysis, and the changing-state and the deviation blocks were analyzed separately. Consistent with the results of Sörqvist (2010), serial recall was disrupted by changing-state distractor sequences compared to the steady-state distractor sequences in the changing-state block, $F(1,141) = 148.07$, $p < .001$, $\eta_p^2 = .51$, and by the deviation distractor sequences compared to the steady-state distractor sequences in the deviation block $F(1,141) = 40.32$, $p < .001$, $\eta_p^2 = .22$ (see Figure

5). Difference scores representing the changing-state effect and the deviation effect were calculated as in the previous experiments and the study of Sörqvist (2010). The changing-state effect ($M = .10$, $SD = .10$) and the deviation effect ($M = .05$, $SD = .09$) correlated significantly with each other, $r = .39$, $p < .001$.

The reliability analysis was based on all steady-state, changing-state, and deviant trials. Due to the fact that there were only six changing-state and deviant trials that were compared to 24 steady-state trials in each block, we first averaged the proportion correct scores for each set of 4 adjacent steady-state trials in each block (e.g. steady-state trial 1 to 4, 5 to 8, etc., were averaged). Subsequently, the corresponding changing-state and deviant trials were subtracted from these measures (e.g. Trial 1 in the changing-state condition was subtracted from the averaged steady-state score from Trials 1-4 in the changing-state block), which resulted in 12 difference scores for the changing-state effect and 12 differences scores for the deviation effect, which were then used to calculate Cronbach's alpha. Cronbach's alpha was $\alpha = .51$ for the changing-state effect and $\alpha = .31$ for the deviation effect.

Relationship between WMC and auditory distraction

As in the original study of Sörqvist (2010), there was no significant correlation between the operation span score and the changing-state effect, $r = .12$, $p = .93$ (see upper panel of Figure 6). However, in contrast to the original experiment of Sörqvist (2010), the correlation between the operation span score and the deviation effect was not significant, too, $r = .09$, $p = .85$ (see lower panel of Figure 6). The descriptive tendency is even in the direction of a positive relationship between WMC and auditory distraction in both conditions (in the opposite direction of prediction). A direct comparison between the correlation of the operation span score with the changing-state effect on the one hand and between the operation span score with the deviation effect on the other hand yielded a non-significant result, *Williams'* $t(139) = 0.32$, $p = .37$.

A supplementary (directional) Bayesian analysis yielded Bayes factors of $BF_{01} = 22.70$ for the correlation between WMC and the changing-state effect and $BF_{01} = 18.26$ for the correlation between WMC and the deviation effect, which indicates that the observed data are 22.70 times (changing-state effect) and 18.26 times (deviation effect) more likely under the null hypothesis than under the alternative hypothesis.

As in the study of Sörqvist (2010), regression analyses were performed in which changing-state performance was used as the dependent variable and performance in the corresponding steady-state condition and the WMC score were used as independent variables. A significant part of the variance in the changing-state performance was explained by the corresponding steady-state performance ($R^2 = .63$, $F[1,140] = 234.98$, $p < .001$), but entering the operation span score in the second step did not lead to a significant increase in the amount of explained variance ($\Delta R^2 < .001$, $\Delta F[1,139] = .08$, $p = .$

78), showing that the operation span scores were not significantly related to the variance in the changing-state performance that was not already explained by the steady-state performance. A significant part of the variance in the deviation performance was explained by the corresponding steady-state performance ($R^2 = .71$, $F[1,140] = 334.06$, $p < .001$), but entering the WMC score in the second step did not lead to a significant increase in the amount of explained variance ($\Delta R^2 < .001$, $\Delta F[1,139] < .001$, $p = .87$), showing that the operation span score was not significantly related to the variance in the deviation performance that was not already explained by the steady-state performance.

The regression residuals were estimated as in Experiment 2. Trials were averaged as when calculating the difference scores, and the resulting scores in the steady-state condition were regressed on the corresponding changing-state and deviation trials to obtain the regression residuals, which were then used to calculate Cronbach's alpha. Cronbach's alpha of the residuals was $\alpha = .60$ for the changing-state effect and $\alpha = .48$ for the deviation effect.

Discussion

In showing that WMC was unrelated to both the changing-state effect and the deviation effect, the results of Experiment 3 (which represents a close replication of

Experiment 1 of Sörqvist, 2010), together with those from Experiments 1 and 2 disconfirm the hypothesis that WMC is differentially related to the changing-state effect and to the deviation effect.

The effect size of the deviation effect ($\eta_p^2 = .22$) was similar to that obtained in the present Experiment 2 ($\eta_p^2 = .27$), which is comparable to the effect sizes reported in other studies (e.g., Hughes et al., 2005, 2007). Given that we used twice as many trials as Sörqvist (2010) to increase the reliability of the distraction scores, it seems sensible to examine whether or not a more direct replication would have yielded different results. When only the first two blocks of the serial recall trials were examined (which represents a direct replication of the data collected by Sörqvist, 2010), both the changing-state effect ($F[1,141] = 121.30$, $p < .001$, $\eta_p^2 = .46$) and the deviation effect ($F[1,141] = 25.39$, $p < .001$, $\eta_p^2 = .15$) were somewhat smaller than when all four blocks were analyzed ($\eta_p^2 = .51$ and $\eta_p^2 = .22$ for the changing-state and the deviation effect, respectively). As expected, the reliabilities of the difference scores were somewhat smaller when only the first two blocks instead of all four blocks were included in the analysis (Cronbach's alpha was $\alpha = .25$ instead of $\alpha = .51$ for the changing-state effect and $\alpha = .26$ instead of $\alpha = .31$ for the deviation effect), but the statistical conclusions were the same when only the first two blocks are considered. Therefore, this aspect of the procedure (which represents the only obvious methodological difference to the original study) is not responsible for the absence of a negative relationship between WMC and the deviation effect in the present study.

Given that the present Experiments 1 and 2 differed from the study of Sörqvist (2010) in some aspects of the materials and the procedure, it was a priori unclear whether we may have unintentionally created less optimal conditions for detecting a negative relationship between the deviation effect and WMC. Given that Experiment 3 is a close replication of the study of Sörqvist (2010), with a rather large sample size (*N* = 142), it is not subject to this problem. Nevertheless, the results of Experiment 3 closely replicate those of the present Experiments 1 and 2, and disconfirm the hypothesis of a negative relationship between WMC and the deviation effect. Of course, there is no such thing as a truly "exact" replication (Simons, 2014) because any two studies will differ in some respects (e.g. we tested German instead of Swedish participants, in a different year, in a different room, etc.)—and the reasons for the discrepancy in the results are unclear—, but there is currently no theory which predicts that the remaining differences between studies should play a role, and effects that vitally depend on such subtle differences in methodology are arguably of little theoretical interest.

General Discussion

One of the most widely accepted accounts of auditory distraction to date—the duplex-mechanism account (Hughes, 2014)—is based on the assumption that there are two functionally distinct types of auditory distraction. The changing-state effect is assumed to be due to automatic processing of the distractor material, and, therefore, to be unaffected by cognitive control. The deviation effect is assumed to be caused by attentional orienting, which is assumed to be open to cognitive control. One prediction of this model is that WMC is unrelated to the changing-state effect but negatively related to the deviation effect (Hughes et al., 2013; Sörqvist, 2010). This assumption is seemingly supported by a small number of studies (Hughes et al., 2013, Sörqvist, 2010) that are repeatedly cited as evidence for a dissociation between the changing-state effect and the deviation effect. However, these studies have comparatively small sample sizes in which sample correlations are known to be variable and inaccurate (Schönbrodt & Perugini, 2013) and effect sizes may be exaggerated (Button et al., 2013). Furthermore, a direct statistical test of the difference between the correlations has not been applied.

Therefore, further (and more direct) tests of the hypothesis that WMC is differentially related to changing-state effect and deviation effect are needed. With respect to the changing-state effect, our findings are in line with previous studies showing that the size of the effect is unrelated to inter-individual differences in WMC (Hughes et al., 2013; Röer et al., 2015; Sörqvist, 2010; Sörqvist et al., 2013). However, WMC was also unrelated to the deviation effect, which is in line with a recent large-sample study by Röer et al. (2015), but inconsistent with earlier small-sample studies

(Hughes et al., 2013, Sörqvist, 2010). This result was obtained although the present experiments provide a comparatively fair test of the hypothesis that WMC is negatively related to the deviation effect: our experiments had larger sample sizes—and, therefore, higher statistical power—than previous experiments (Hughes et al., 2013, Sörqvist, 2010). Furthermore, we used a composite WMC score instead of single complex-span tasks, which should increase the psychometric properties of the WMC measure. We also applied directional (one-sided) tests in all analyses, in contrast to most previous studies (Sörqvist, 2010, Röer et al., 2015). All of these factors should have made it easier to detect a negative relationship between WMC and the deviation effect if it existed. Nevertheless, there was no evidence that individuals with high WMC were better at ignoring any type of auditory distraction than individuals with low WMC. Most importantly, a direct test disconfirmed the hypothesis that the correlation between WMC and the changing state effect differed significantly from that between WMC and the deviation effect, which provides direct evidence against a dissociation between those two forms of auditory distraction.

A potential concern may be that the samples consisted only of students. It is well known that—all other factors being held constant—a correlation between WMC and any other variable is easier to find when there is a wide range of WMC scores than when there is a restricted range of WMC scores (Goodwin & Leech, 2006). Although there was considerable variation of the WMC scores in our student samples (see Figures 2, 4, and 6), we cannot exclude the possibility that there were fewer individuals with extremely low WMC scores in the student samples in comparison to other samples, which could have restricted the range of WMC scores obtained. However, the same limitation applies to the studies of Hughes et al. (2013) and Sörqvist (2010)—in which only student samples were tested—which means that restriction of range cannot explain the discrepancies in the results.

A notable exception is the study of Röer et al. (2015), in which a student sample of young adults was compared with a community sample of older adults. A wide range of operation span scores was found when the data of the young and older adults were combined in a single analysis. Given that the results related to inter-individual differences in WMC were only mentioned briefly by Röer et al. (2015) because the main focus of that study was on age differences in distractibility (and not on the relationship between WMC and distractibility), it seems useful to provide a more detailed analysis and discussion of these data here. The relationship between operation span[6] and the changing-state effect on the one hand and the deviation effect on the other is illustrated in Figure 7.

As in the present Experiments 1 and 3 as well as in the condition with the

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[6] Only a single operation span task was used as a measure of WMC (for a detailed description of the tasks, see Röer et al., 2015).

balanced amount of trials in every condition in Experiment 2, there was a significant positive correlation between the changing-state effect (*M* = .06, *SD* = .11) and the deviation effect (*M* = .04, *SD* = .10; *r* = .36, *p* < .001). Consistent with the present and previous results, the correlation between operation span and the changing-state effect was not significant, *r* = .01, *p* = .57. The same was true for the correlation between operation span and the deviation effect, *r* = -.04, *p* = .25. When compared directly, the difference between these two correlations was not significant even when tested with a one-sided test, *Williams' t*(255) = 0.73, *p* = .23. A supplementary (directional) Bayesian analysis yielded Bayes factors of BF_{01} = 14.53 for the correlation between WMC and the changing-state effect and BF_{01} = 6.83 for the correlation between WMC and the deviation effect, which indicates that the observed data are 14.53 times (changing-state effect) and 6.83 times (deviation effect) more likely under the null hypothesis than under the alternative hypothesis. These analyses provide evidence that inter-individual differences in a complex span task do not show a negative relationship with the deviation effect even when there is a wide range of inter-individual variation in WMC in the sample, as evidenced by the operation span scores shown in Figure 7. This is noticeable insofar as the high degree of inter-individual variation should have increased the probability of finding such a relationship between WMC and the deviation effect in comparison to previous studies (Hughes et al., 2013, Sörqvist, 2010). Nevertheless, the study provided evidence that WMC is unrelated to both the changing-state effect and the deviation effect.

We also followed the advice of a reviewer and examined whether the correlation between the deviation effect and WMC would differ from zero when the data of all four experiments—the present Experiments 1, 2, 3, and that of Röer et al., (2015)—were combined. Given that different versions of the operation span task were used in Experiments 1 and 2, Experiment 3, and Röer et al.'s (2015) study, this analysis was based on z-transformed operation span scores. With a total sample size of $N = 601$ and $\alpha = \beta = .05$, a potential correlation as small as $\rho = .13$ could be detected, if there was one. However, despite that the power was sufficiently high ($1 - \beta = .95$) to detect even a small effect, the operation span scores did not correlate with either the changing-state effect ($r = .05$, $p = .88$) or the deviation effect ($r =.02$; $p = .67$). These correlations also did not differ from each other, *Williams'* $t(598) = 0.63$, $p = .26$. Thus, the conclusion that there is no dissociation between changing-state effect and deviation effect was confirmed even with this very large sample size.

The present study therefore disconfirms that changing-state effect and deviation effect differ in their relationship to WMC. As mentioned in the Introduction, the changing-state effect and the deviation effect share a number of features—both refer to a disruption of short term memory by abrupt auditory changes—that make them appear similar in nature. Given that a unitary explanation is to be preferred based on the criterion of parsimony alone (Hughes et al., 2005, 2007), the duplex-mechanism account crucially depends on the empirical evidence in favor of dissociations to justify why it is necessary to postulate fundamentally different mechanisms to explain two phenomena that are so similar at the surface. The present results weaken the empirical basis of the duplex-mechanism account by providing evidence against one of the dissociations that form its empirical core (Hughes, 2014).

Of course, the duplex-mechanism account, as all good theories, integrates a large number of findings (for a review, see Hughes, 2014). Therefore, the theory should not be judged on the basis of a single empirical finding. However, the theory has become the standard model for explaining auditory-distraction effects over the last years (e.g. Elliott et al., 2016; Röer et al., 2013; Schwarz et al., 2015; Sörqvist, 2010), and the present findings indicate that further tests are necessary before alternative, simpler accounts are dismissed. Due to the breadth of the available evidence, an in-depth-discussion of the model and its empirical basis is beyond the scope of the present paper (for a more complete review of the available evidence in support of the duplex-mechanism account, see Hughes, 2014). Empirical arguments in favor of the duplex-mechanism accounts' key assumption of a dissociation of the changing-state and the deviation effect (Hughes et al., 2005, 2007, 2013) include the following findings: (1) The deviation effect was abolished when the distractors were played during a retention interval while the changing-state effect was present independently of whether the distractors were presented during target item presentation or retention (Hughes et al., 2005; but see Röer et al., 2014b for contradicting evidence). (2) The deviation effect has been found in tasks such as the missing-item task in which no changing-state effect was found (Hughes et al., 2007). (3) It has also been argued that the deviation effect is prone to habituation while the changing-state effect is not (Sörqvist, 2010, but see Röer et al., 2014a, for contradicting evidence). (4) Perceptual masking eliminated the deviation effect and did not affect the changing-state effect (Hughes et al., 2013). (5) Providing a warning that a deviation sequence was about to be presented in the following trial reduced the deviation effect, but a similar unspecific warning about upcoming changing-state sequences did not affect the changing-state effect (Hughes et al., 2013; but see Röer, Bell, & Buchner, 2015 for contradicting evidence). (6) The changing-state effect and the deviation effect were additive when co-manipulated and did not under-additively interact as would be expected if they were underpinned by the same mechanism (Hughes et al., 2007). Taken together, these and other findings seem to provide compelling support for the duplex-mechanism account.

While the evidence in favor of the duplex-mechanism account should not be too easily dismissed, it should not be considered definitive either. The evidence is more mixed than usually admitted. To illustrate, although it has been claimed that "a large body of evidence demonstrated habituation toward the disruptive effects of deviating sounds on task performance (…), but people seem unable to habituate to the effects of changing- state sound sequences on serial recall" (Sörqvist, 2010, p. 651f), there is no evidence for a differential habituation rate when the changing-state condition and the deviation condition are directly compared (Röer, Bell, Marsh, et al., 2015). What is more, the evidence in favor of dissociations often relies on comparisons between different experiments, sometimes even involving different methodological approaches (Röer et al., 2014b; Röer, Bell, & Buchner, 2015, for detailded discussion of examples). This means that a significant effect in one experiment and a nonsignificant effect in another experiment are interpreted as evidence of a dissociation. To provide useful evidence in favor of a dissociation, it is mandatory to compare the two phenomena directly, as in the present study. Furthermore, arguments in favor of the duplex-mechanism account often involve auxiliary assumptions that could turn out to be too simplistic such as that attentional capture is an all-or-nothing process (Hughes et al., 2007). We conclude that more, and more direct, evidence is necessary before alternative, simpler accounts can be confidently ruled out.

The main aim of the present study was to test the prediction of the duplex-mechanism account that there is a dissociation between the changing-state effect and the deviation effect. However, the present findings are relevant for the unitary attentional account (Cowan, 1995) as well. According to this model, the changing-state effect and the deviation effect are based on the same cognitive mechanism (attentional capture), which leads to the prediction that (1) both effects should be positively correlated which each other and (2) both effects should be similarly related to WMC. Both predictions were supported by the present results. It is more difficult to draw clear predictions about the direction of the relationship between WMC and the two types of auditory distraction. Usually, this model is interpreted as predicting a negative correlation between WMC and auditory distraction (Elliott, 2002; Elliott & Cowan, 2005; Hughes et al., 2013; Sörqvist, 2010; Sörqvist, Marsh, & Nöstl, 2013). For example, it has been shown that persons with high WMC are less likely to detect their own name in an unattended auditory channel in a dichotic-listening paradigm than persons with low WMC (Conway et al., 2001), which was interpreted as supporting the view that individuals with high WMC have better attentional control abilities (Engle, 2002). Against this background, it might seem surprising that WMC was related neither to the changing-state effect nor to the deviation effect. However, the situation in the two tasks —the dichotic listening task and the serial recall task—are different. The dichotic listening task requires participants to voluntarily focus on one auditory stream while ignoring another stream within the same modality. This cognitive process is thought to be different from situations such as the serial recall task in the present study in which the relevant and the irrelevant information are presented in different modalities and in which the irrelevant information could be blocked off at early stages of processing (Guerreiro et al., 2010) in principle.

It is also important to note that it depends on one's view of the nature of WMC whether a correlation between auditory distraction and WMC is to be expected (see Introduction). For example, when WMC is viewed as reflecting the ability to rehearse and maintain material (Unsworth & Engle, 2007), it is even possible to entertain the possibility of a positive correlation between WMC and auditory distraction because more rehearsal may provide more opportunity for disruption (see Elliott & Cowan, 2005).

Finally, it seems useful to consider the possibility that the orienting of attention to to-be-ignored auditory information is not caused by a defective system that is incapable of preventing the processing of information from an entirely irrelevant channel (that could be easily filtered out at early stages of processing, see Guerreiro et al., 2010). Instead, it may be an adaptive mechanism that serves to guarantee that the system remains open for information that is of great relevance for one's long-term goals such as survival (e.g., detecting a fire alarm while reading). Recent developmental evidence supports such a view. In particular, deviance distraction and WMC were positively—not negatively—related in children, which suggests that deviation distraction may be a functionally important mechanisms that matures with increasing age in children (Leiva, Andres, Servera, Verbruggen, & Parmentier, 2016).

Conclusions

The experiments reported here were designed to test the prediction of the duplex-mechanism account (Hughes et al., 2013) that the changing-state effect and the deviation effect should be differentially related to WMC. The present results clearly disconfirm that there is such a dissociation. In fact, WMC was neither correlated with the changing-state nor with the deviation effect, and no difference was found between these correlations. These results are supported by a detailed reanalysis of data from a previous cognitive-ageing study (Röer et al., 2015). Together with other results, these findings challenge the idea that there are two fundamentally different mechanisms of auditory distraction that can be dissociated from each other. Therefore, unitary explanations of auditory distraction should not be prematurely dismissed.

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Tables

Table 1. Descriptive statistics for the working memory tasks in Experiment 1, Experiment 2 and Experiment 3.

	M	*SD*	Minimum	Maximum
Experiment 1				
Operation Span	0.76	0.13	0.30	0.99
Sentence Span	0.79	0.15	0.35	1.00
WMC score	0.77	0.12	0.38	0.97
Experiment 2				
Operation Span day 1	0.76	0.12	0.37	0.97
Operation Span day 2	0.82	0.12	0.33	1.00
Sentence Span day 1	0.81	0.13	0.50	0.99
Sentence Span day 2	0.86	0.11	0.37	1.00
WMC score	0.81	0.10	0.52	0.97
Experiment 3				
Operation Span	0.84	0.11	0.42	1.00

Figures

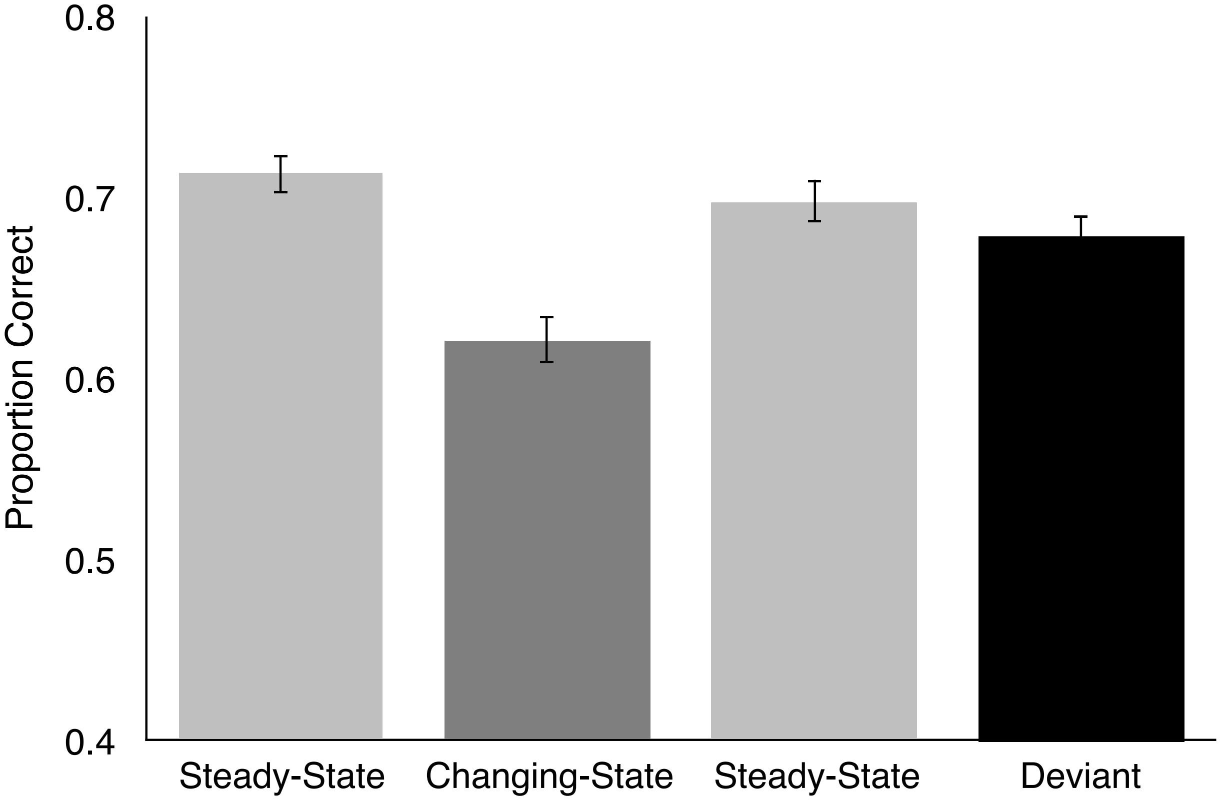

Figure 1. Proportion of correct responses in the serial recall task of Experiment 1 as a function of distractor type in the changing-state block (steady-state vs. changing state, left bars) and in the deviation block (steady-state vs. deviation sequences, right bars). The error bars represent the standard errors of the means.

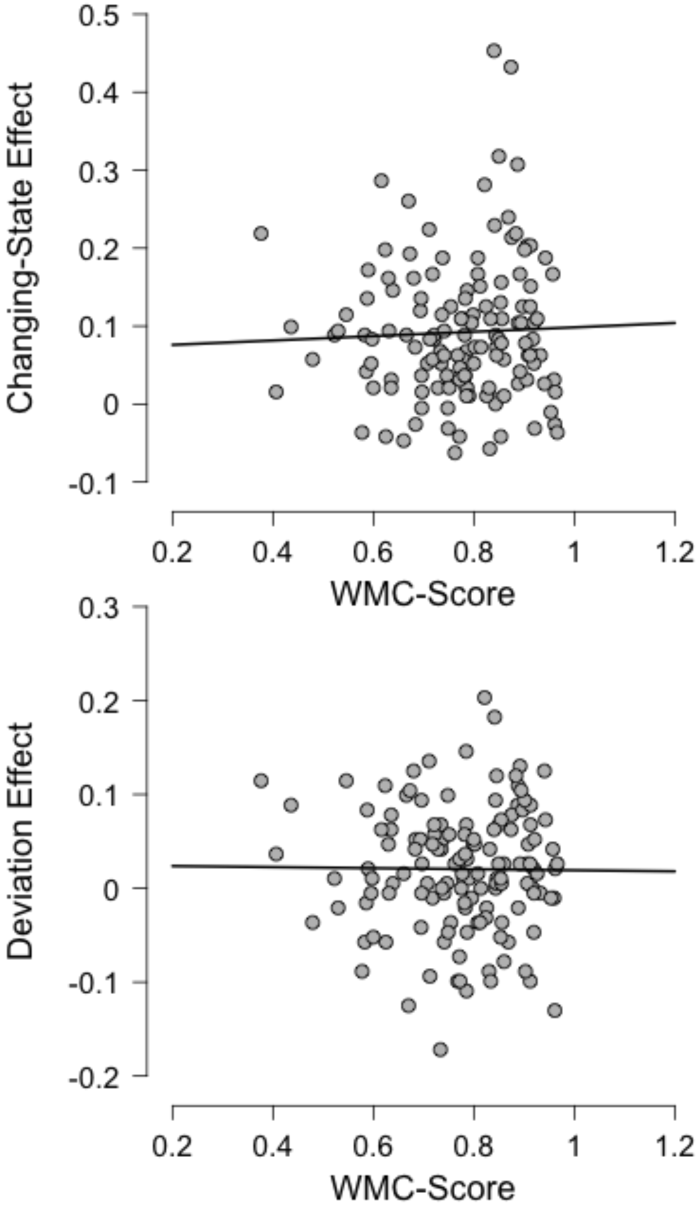

Figure 2. The correlation between the WMC score and the changing-state effect (calculated as the difference between the serial recall performance in the steady-state and the changing-state condition, upper panel) and the correlation between the WMC score and the deviation effect (calculated as the difference between the serial recall performance in the steady-state and the deviation condition, bottom panel) in Experiment 1. The Figure was produced using JASP (available on https://jasp-stats.org).

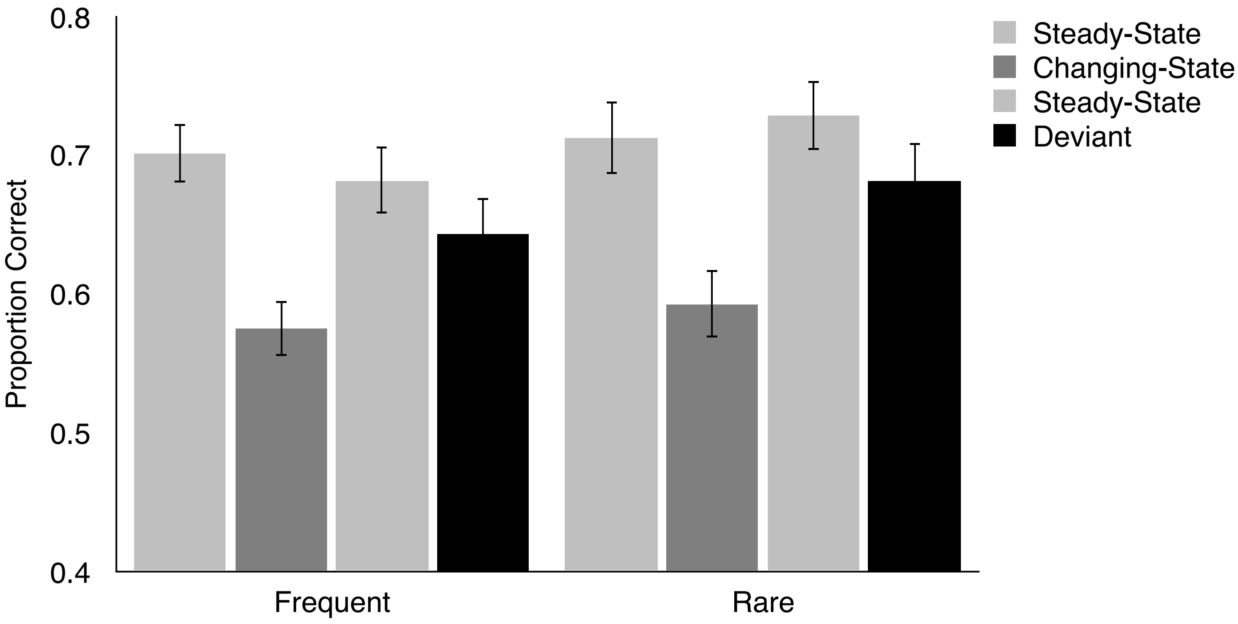

Figure 3. Proportion of correct responses in the serial recall task of Experiment 2 as a function of frequency (frequent vs. rare), distractor type in the changing-state block (steady-state vs. changing state) and in the deviation block (steady-state vs. deviation sequences). The error bars represent the standard errors of the means.

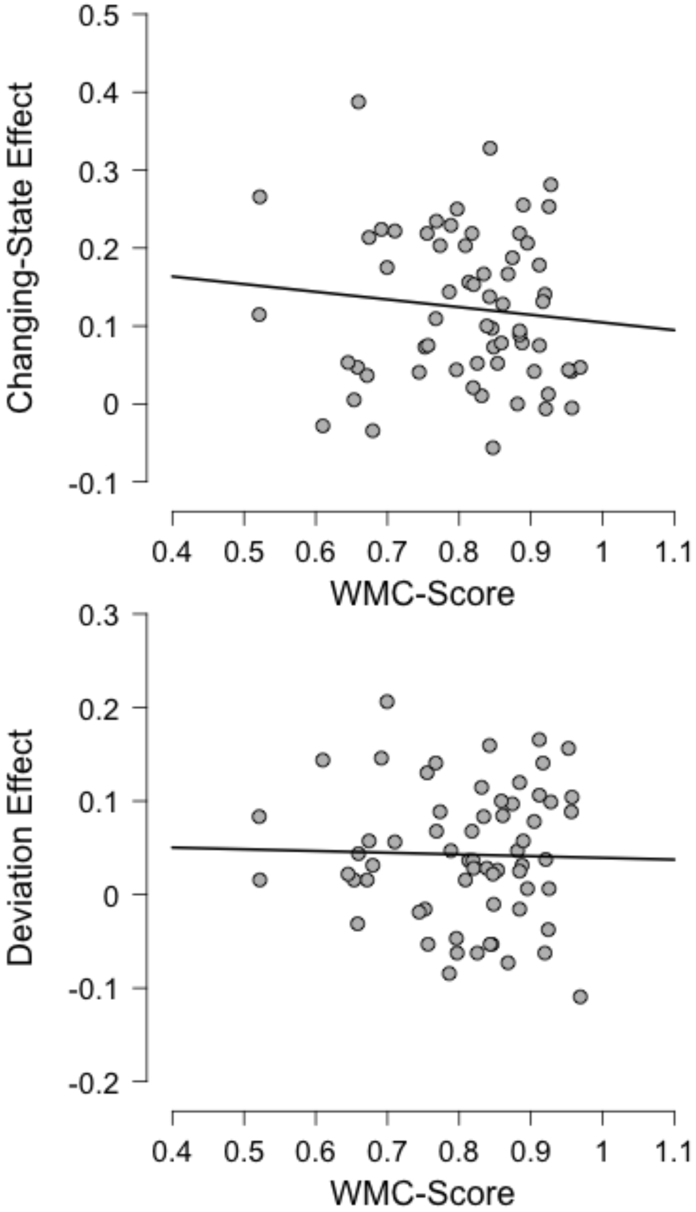

Figure 4. The correlation between the WMC score and the changing-state effect (calculated as the difference between the serial recall performance in the steady-state and the changing-state condition, upper panel) and the correlation between the WMC score and the deviation effect (calculated as the difference between the serial recall performance in the steady-state and the deviation condition, bottom panel) in Experiment 2. The figure was produced using JASP (available on https://jasp-stats.org).

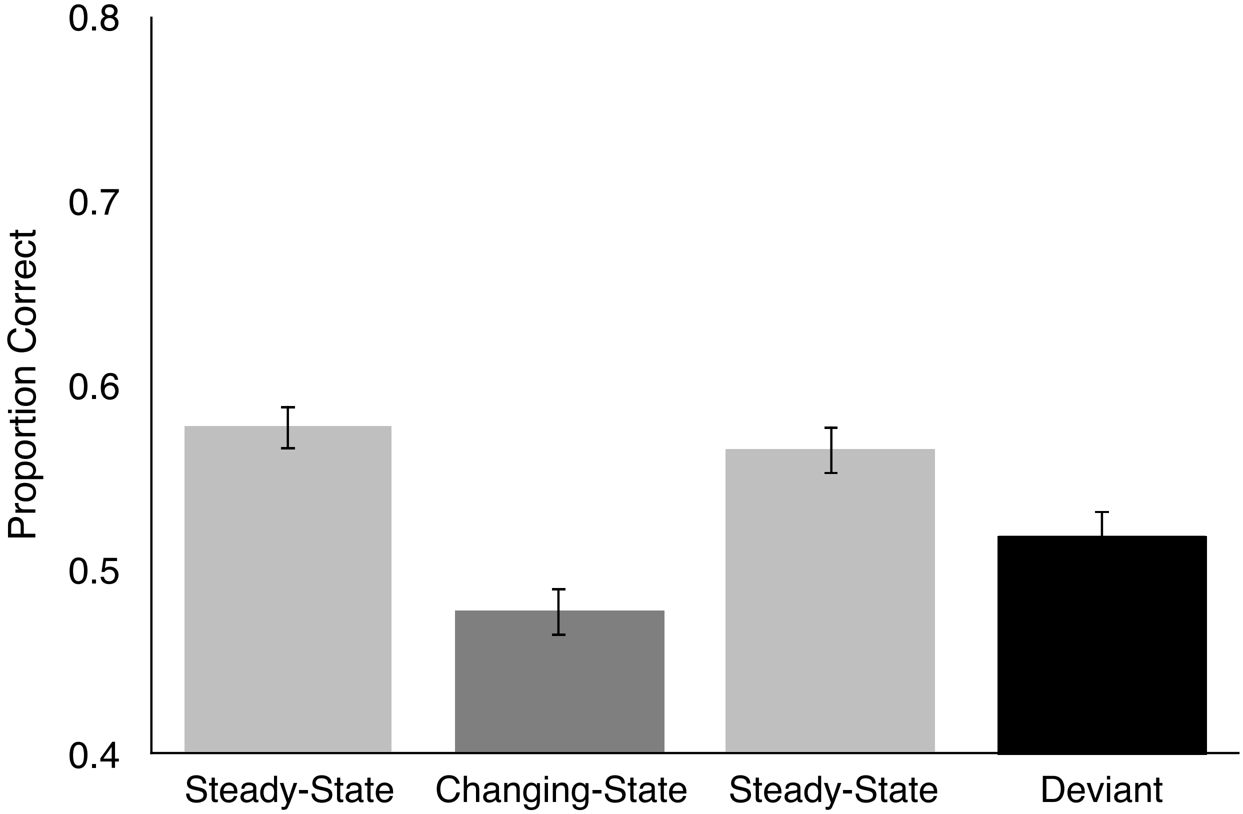

Figure 5. Proportion of correct responses in the serial recall task of Experiment 3 as a function of distractor type in the changing-state block (steady-state vs. changing state, left bars) and in the deviation block (steady-state vs. deviation sequences, right bars). The error bars represent the standard errors of the means.

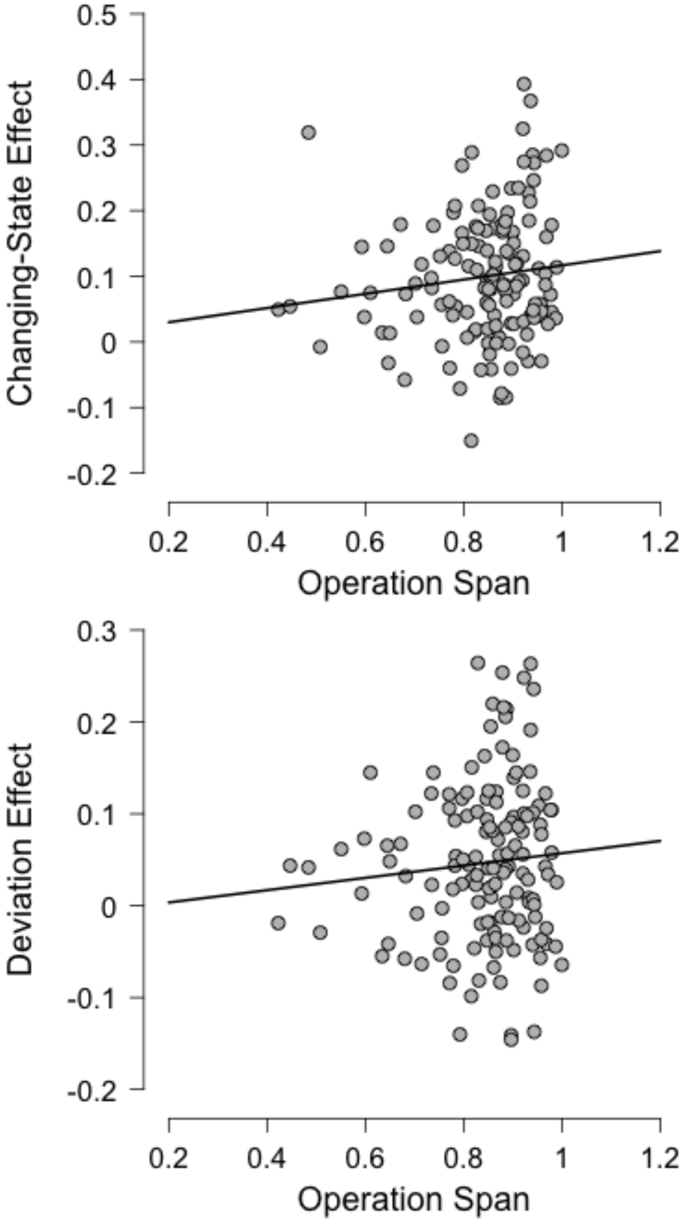

Figure 6. The correlation between the operation span score and the changing-state effect (calculated as the difference between the serial recall performance in the steady-state and the changing-state condition, upper panel) and the correlation between the operation span score and the deviation effect (calculated as the difference between the serial recall performance in the steady-state and the deviation condition, bottom panel) in Experiment 3. The figure was produced using JASP (available on https://jasp-stats.org).

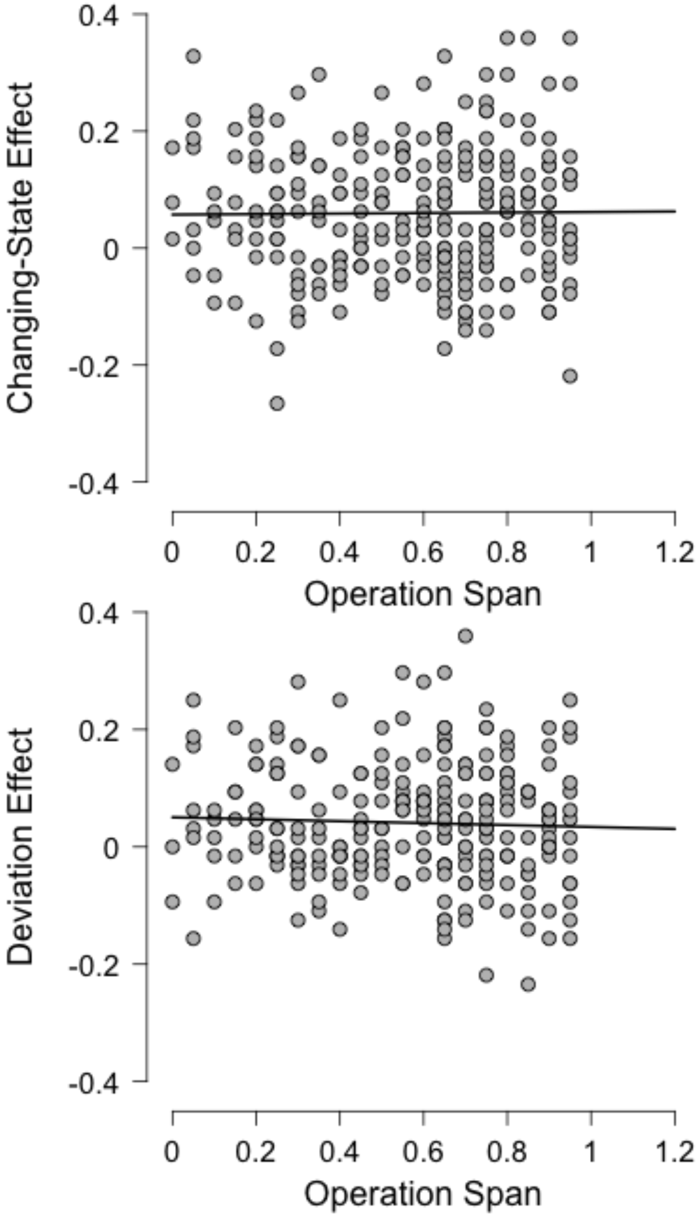

Figure 7. The correlation between the operation span score and the changing-state effect (calculated as the difference between the serial recall performance in the steady-state and the changing-state condition, upper panel) and the correlation between the operation span score and the deviation effect (calculated as the difference between the serial recall performance in the steady-state and the deviation condition, bottom panel) in Röer et al. (2015). The figure was produced using JASP (available on https://jasp-stats.org).