Der Einfluss des Präsentations-zeitpunktes und der Arbeitsgedächtnis-kapazität auf die Störwirkung wechselhafter und devianter auditiver Distraktoren: Ein Modelltest

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Zusammenfassung

Aufgabenirrelevante Hintergrundgeräusche haben einen negativen Einfluss auf die serielle Reproduktionsleistung. Während ein Konsens darüber besteht, dass die Störwirkung von Hintergrundgeräuschen hauptsächlich durch akustische Reizeigenschaften determiniert ist, ist es auf theoretischer Ebene umstritten, welche Arbeitsgedächtnisprozesse durch Hintergrundgeräusche beeinträchtigt werden. Das Duplex-Modell basiert auf der Annahme, dass es zwei funktionell verschiedene Arten auditiver Ablenkung gibt. Die Ablenkung durch wechselhafte *Changing-State*- im Vergleich zu repetitiven *Steady-State*-Sequenzen (der *Changing-State*-Effekt) wird auf automatische Interferenz zwischen der Verarbeitung von Reihenfolgeinformationen von Ziel- und Distraktorreizen zurückgeführt. Im Gegensatz dazu wird die größere Störwirkung von Sequenzen mit einem einzelnen abweichenden Distraktor im Vergleich zu *Steady-State*-Sequenzen (der Devianz-Effekt) über Aufmerksamkeitsablenkung erklärt. Laut dem *Embedded-Processes*-Modell hingegen basieren der *Changing-State*- und der Devianz-Effekt auf demselben kognitiven Mechanismus der Aufmerksamkeitsablenkung. Obwohl der Ansatz des *Embedded-Processes*-Modells allein aufgrund der Sparsamkeit seiner Annahmen zu bevorzugen ist, wird die Annahme einer Dissoziation der beiden Effekte mit Befunden gerechtfertigt, die für eine solche Dissoziation sprechen. Diese Befunde sind jedoch mindestens teilweise unzureichend empirisch gesichert. Ziel der vorliegenden Arbeit war es daher, zwei vom Duplex-Modell zentral postulierte Dissoziationen zwischen *Changing-State*- und Devianz-Effekt – die unterschiedliche Beeinflussung von Enkodierungs- und Gedächtnisprozessen sowie den unterschiedlichen Zusammenhang der beiden Effekte zur Arbeitsgedächtniskapazität – systematisch zu testen.

In den Experimenten 1a, 1b, 2a und 2b wurde die Vorhersage des Duplex-Modells überprüft, dass *Changing-State*-Sequenzen nur die Aufrechterhaltung von Informationen bei der seriellen Reproduktion stören, während deviante Sequenzen selektiv mit deren Enkodierung interferieren. *Changing-State*- und deviante Distraktoren wurden dazu in einem von vier Präsentationsintervallen während der seriellen Reproduktion präsentiert: (1) in der ersten Hälfte der Präsentationsphase, (2) in der zweiten Hälfte der Präsentationsphase, (3) in der ersten Hälf-

te der Retentionsphase und (4) in der zweiten Hälfte der Retentionsphase. Entgegen der Vorhersage des Duplex-Modells zeigte sich, dass die Darbietung beider Arten von Distraktoren sowohl in der Präsentations- als auch in der Retentionsphase zur Beeinträchtigung der seriellen Reproduktion führten, wobei der größte Effekt beobachtet werden konnte, wenn die Sequenzen in der zweiten Hälfte der Präsentationsphase dargeboten wurden, einem Intervall, in dem die Aufrechterhaltung der Zielreize mit der Enkodierung weiterer Zielreize koordiniert werden muss.

Die Experimente 3, 4 und 5 dienten der Überprüfung der Vorhersage, dass es einen negativen Zusammenhang zwischen der Arbeitsgedächtniskapazität und dem aufmerksamkeitsbasierten Devianz-Effekt geben sollte, bei ausbleibendem Zusammenhang zwischen der Arbeitsgedächtniskapazität und dem *Changing-State*-Effekt, der auf automatischer Interferenz basiert und daher unbeeinflusst von kognitiver Kontrolle sein sollte. Im Widerspruch zu den Vorhersagen des Duplex-Modells lieferten die Experimente keine Evidenz für eine Dissoziation der beiden Effekte. Die Arbeitsgedächtniskapazität korrelierte weder mit dem *Changing-State*- noch mit dem Devianz-Effekt und es zeigte sich kein Unterschied zwischen den Korrelationen.

Die Befunde sprechen daher klar gegen eine funktionale Dissoziation der beiden Effekte und stellen den Gültigkeitsanspruch des Duplex-Modells in Frage, welches auf der Grundannahme zweier unterschiedlicher kognitiver Prozesse zur Erklärung der beiden Effekte basiert. Besser lassen sich diese Ergebnisse mit den Annahmen des *Embedded-Processes*-Modells erklären, laut dem beide Effekte auf dem gleichen kognitiven Prozess der Aufmerksamkeitsablenkung beruhen und ähnliche Arbeitsgedächtnisprozesse beeinträchtigen.

Abstract

It is well established that task-irrelevant background sound adversely affects serial short-term memory for visually presented items. While there is a general consensus that auditory distraction is mainly determined by acoustic characteristics of the auditory material there is an ongoing debate on the cognitive mechanisms that underlie negative effects of background sound on cognitive performance. The duplex-mechanism account is based on the assumption that there are two functionally distinct types of auditory distraction. Distraction by variable changing-state sequences (the changing-state effect) is thought to be based on automatic interference between the processing of order information of the target and the distractor material. By contrast, the disruptive power of sequences with a single deviating item (the deviation effect) is explained by attentional capture. An alternative explanation is offered by the embedded-processes model that states that the changing-state effect and the deviation effect are both based on the same cognitive process – attentional capture. While the latter view is to be preferred based on its parsimony alone, the theoretical dissociation of both distraction effects is justified by empirical evidence that supports this dissociation. However, this evidence relies on methodologically problematic experimental designs. Therefore, the aim of the present thesis was to systematically test the core assumptions of the duplex account by examining two postulated dissociations of that account: the differential influence of time of presentation and individual working memory capacity on the changing-state effect and the deviation effect.

Experiments 1a, 1b, 2a and 2b aimed at testing the prediction of the duplex account that changing-state distractors should interfere only with the rehearsal of target items in working memory while deviant distractors should only interfere with the encoding. In these experiments, changing-state and deviant distractor sounds were presented in one of four presentation intervals of the serial recall task: (1) during the first half of encoding, (2) during the second half of encoding, (3) during the first half of retention, or (4) during the second half of retention. Inconsistent with the assumption of the duplex account, both types of distractors interfered with the encoding and the retention of target items in working memory. These effects were most pronounced when the distractors were presented during the second half of enco-

ding which is when the encoding of target items and the simultaneous maintenance of already presented targets pose a high burden on working memory.

In Experiment 3, 4 and 5 the prediction of the duplex account that individual working-memory capacity (WMC) is differentially related to the changing-state effect (no correlation) and the deviation effect (negative correlation) was examined. In contrast to this prediction, there was no evidence of a dissociation of both effects as WMC was neither correlated with the changing-state effect nor with the deviation effect, and these correlations did not significantly differ from each other.

These results clearly contradict the core assumption of the duplex account that the changing-state effect and the deviation effect are based on functionally different cognitive mechanisms. The results are more in line with the assumptions of the embedded-processes model that both effects depend on attentional processes and disrupt similar working memory mechanisms.

Einleitung

Kognitive Aufgaben wie Lesen, Lernen oder Kopfrechnen werden im Alltag häufig in Anwesenheit von Hintergrundgeräuschen ausgeführt. Dabei ist bekannt, dass aufgabenirrelevante Geräusche einen negativen Einfluss auf die kognitive Leistung haben (Bell, Dentale, Buchner, & Mayr, 2010; Campbell, Beaman, & Berry, 2002; Colle & Welsh, 1976; Jones, Madden, & Miles, 1992; Parmentier, 2014; Röer, Bell, Dentale, & Buchner, 2011; Vachon, Hughes, & Jones, 2012). Ein besonders gut untersuchtes Phänomen der Beeinträchtigung kognitiver Leistungsfähigkeit durch Umgebungsgeräusche ist der *Irrelevant-Sound*-Effekt. Er beschreibt die Beobachtung, dass aufgabenirrelevante Hintergrundgeräusche die serielle Reproduktion von nacheinander präsentierten Zielreizen (Zahlen, Buchstaben oder Wörtern) im Vergleich zu einer Ruhebedingung beeinträchtigen (Bell et al., 2010; Colle & Welsh, 1976; Jones & Macken, 1993; Marsh, Hughes, & Jones, 2009; Miles, Jones, & Madden, 1991; Röer, Körner, Buchner, & Bell, in press). Im klassischen Experimentalablauf geht es darum, visuell nacheinander präsentierte Zielreize direkt oder nach einer kurzen Retentionsphase in der Reihenfolge ihrer Präsentation zu reproduzieren, während Hintergrundgeräusche ignoriert werden sollen. Es besteht Konsens darüber, dass das Ausmaß der Störwirkung von aufgabenirrelevantem, auditivem Material (z.B. Buchstaben, Wörter, Sätze, Töne oder Melodien) maßgeblich durch seine Variabilität, das heißt abrupte Veränderungen physikalischer Reizeigenschaften, determiniert wird (Ellermeier & Zimmer, 2014; Schlittmeier, Weisgerber, Kerber, Fastl, & Hellbrück, 2012; Tremblay & Jones, 1999). Dementsprechend werden drei verschiedene Arten von Hintergrundschallen unterschieden, die einen unterschiedlich großen Einfluss auf die serielle Reproduktionsleistung haben. Zur geringsten Leistungsbeeinträchtigung führt die Präsentation von Sequenzen ohne akustische Veränderungen, sogenannten *Steady-State*-Sequenzen, die aus einer Wiederholung eines einzelnen Distraktors (z.B. A A A A A A A A) bestehen (Bell et al., 2010; Jones & Macken, 1993; LeCompte, 1995). Im Vergleich zu *Steady-State*-Sequenzen führen wechselhafte Distraktorsequenzen, sogenannte *Changing-State*-Sequenzen, die aus verschiedenen Distraktoren (z.B. E G C D A H B F) bestehen, zu einer stärkeren Beeinträchtigung der seriellen Reproduktionsleistung; ein Effekt, der als *Changing-State*-Effekt bezeichnet wird (Bell et al., 2010; Campbell et al., 2002; Jones & Macken, 1993; Jones et al., 1992; Parmentier & Beaman, 2014; Schlittmeier, Hellbrück, & Klatte, 2008). Zu einer stärkeren Störwirkung im Vergleich zu *Steady-State*-Sequenzen führt auch die Darbietung von Sequenzen, innerhalb derer ein einzelner Distraktor vom repetitiven Muster der vorausgehenden Stimulation abweicht (z.B. A A A A A B A A). Dieser Effekt wird als Devianz-Effekt bezeichnet (Hughes, Vachon, & Jones, 2005, 2007; Sörqvist, 2010). Trotz offensichtlicher Ähnlichkeit des *Changing-State*- und des Devianz-Effektes – beide Effekte basieren auf der Beeinträchtigung der seriellen Reproduktion durch akustische Abweichungen von einzelnen oder mehreren vorausgegangenen Distraktoren innerhalb einer Sequenz – ist es auf theoretischer Ebene umstritten, inwieweit beide Effekte auf denselben zugrunde liegenden kognitiven Prozessen basieren (Cowan, 1995, 1999; Hughes, 2014; Hughes et al., 2007).

Laut dem *Embedded-Processes*-Modell (Cowan, 1995, 1999) gehen beide Effekte auf eine Aufmerksamkeitsablenkung zurück. In diesem Modell wird angenommen, dass sowohl die Enkodierung neuer als auch die Aufrechterhaltung bereits präsentierter Zielreize bei der seriellen Reproduktion Aufmerksamkeit beanspruchen. Die Aufrechterhaltung der Zielreize erfolgt dabei durch eine kontinuierlich ablaufende Reaktivierung der Reize im Fokus der Aufmerksamkeit (*Rehearsal)*, die diese im Arbeitsgedächtnis hält. Aufgabenirrelevante Distraktoren, die von der vorherigen Stimulation abweichen, unerwartet oder von besonderer Relevanz sind, ziehen automatisch Aufmerksamkeit auf sich und lösen eine Orientierungsreaktion aus. Die Aufmerksamkeit wird von der Enkodierung und Aufrechterhaltung der Zielreize abgelenkt und die Wahrscheinlichkeit eines fehlerfreien Abrufs der Zielreize reduziert. Der *Changing-State*-Effekt wird dadurch erklärt, dass durch die akustischen Veränderungen zwischen aufeinanderfolgenden Distraktoren innerhalb von *Changing-State*-Sequenzen eine wiederkehrende Orientierungsreaktion zu den Distraktoren ausgelöst wird, welche die Aufmerksamkeit von der Primäraufgabe ablenkt. Im Gegensatz dazu fällt die Beeinträchtigung durch *Steady-State*-Sequenzen geringer aus, da eine Habituation an die repetitive Darbietung desselben Distraktors stattfindet, wodurch die initial ausgelöste Orientierungsreaktion auf die auditiven Reize abgeschwächt wird. Der Devianz-Effekt wird über dieselben Mechanismen erklärt. Die abrupte Unterbrechung der regelhaften Sequenz durch einen devianten Distraktor wird vom kognitiven System als Abweichung von einem internen neuronalen Modell der vorangehenden Stimulation detektiert, mit dem Resultat einer Aufmerksamkeitsablenkung auf die auditive Modalität. Diese aufmerksamkeitsbasierte Erklärung auditiver Ablenkung wird durch psychophysiologische Befunde gestützt, in denen im Zusammenhang mit auditiver Ablenkung durch wechselhafte, neuartige und deviante auditive Reize ereigniskorrelierte Potentiale identifiziert werden konnten, die als Korrelate verschiedener Stufen einer Aufmerksamkeitsverschiebung gelten, wie der N1 und der *Mismatch-Negativity* (MMN) als Korrelat einer präattentiven Detektion unerwarteter Veränderungen der akustischen Reizumgebung, der P3a als Zeichen eines Aufmerksamkeitswechsels auf die Distraktorreize und der Reorientierungsnegativität (RON) als Indiz einer Rückorientierung der Aufmerksamkeit auf die visuellen Zielreize (Bell et al., 2010; Campbell, Winkler, & Kujala, 2007; Campbell, Winkler, Kujala, & Näätänen, 2003; Escera, Alho, Schröger, & Winkler, 2000). Innerhalb des *Embedded-Processes*-Modells wird daher die temporäre Aufmerksamkeitsablenkung von den visuellen Zielreizen auf die auditiven Distraktoren als zentraler Mechanismus zur Erklärung sowohl des *Changing-State*- als auch des Devianz-Effektes verstanden.

Eine alternative Erklärung bietet das Duplex-Modell (Hughes, 2014; Hughes et al., 2007), das aktuell als Modell auditiver Ablenkung in der Literatur großen Zuspruch findet (z.B. Klatte, Lachmann, Schlittmeier, & Hellbrück, 2010; Schwarz et al., 2015; Sörqvist, Nöstl, & Halin, 2012; Vachon, Labonté, & Marsh, 2017) und dem die Annahme zugrunde liegt, dass der *Changing-State*- und der Devianz-Effekt auf fundamental verschiedenen Mechanismen beruhen. Entscheidend für die erfolgreiche serielle Reproduktion von Zielreizen ist laut dem Duplex-Modell die Aufrechterhaltung ihrer Reihenfolge durch die Bildung episodischer Verweise zwischen einzelnen Reizen, einem Prozess, der als Seriation bezeichnet wird. Der *Changing-State*-Effekt wird dadurch erklärt, dass die Verarbeitung der Reihenfolgeinformation der Zielreize mit der automatischen Verarbeitung der Reihenfolgeinformation der Distraktorsequenzen interferiert. Aufgrund akustischer Abweichungen zwischen aufeinanderfolgenden Distraktoren werden *Changing-State*-Sequenzen präattentiv und obligatorisch in einzelne Objekte segmentiert und ihre Reihenfolge, mittels episodischer Verweise von einem Item auf das nächste, im Gedächtnis repräsentiert (Jones & Macken, 1993). Da die Zielreize auf dieselbe Weise verarbeitet werden, kommt es zur Interferenz dieser Prozesse und einer Beeinträchtigung der seriellen Reproduktionsleistung. Repetitive *Steady-State*-Sequenzen hingegen werden gemäß des Duplex-Modells nur durch ein einziges, auf sich selbst verweisendes Objekt repräsentiert und enthalten keine Reihenfolgeinformation, was eine Interferenz mit der Aufrechterhaltung der Zielreize ausschließt. Ein Einfluss von Aufmerksamkeit wird bei der Erklärung des *Changing-State*-Effektes explizit ausgeschlossen. Im Gegensatz dazu wird der Devianz-Effekt über eine Aufmerksamkeitsablenkung erklärt. Laut diesem Ansatz führt die Erwartungsverletzung durch einen devianten Distraktor innerhalb einer vorhersagbaren, repetitiven Sequenz zu einer Aufmerksamkeitsablenkung auf die auditive Modalität, wobei davon ausgegangen wird, dass dieser Prozess selektiv die Enkodierung und nicht die Aufrechterhaltung von Zielreizen beeinträchtigt (Hughes et al., 2005).

Die direkte Gegenüberstellung beider Modelle lässt den Ansatz des *Embedded-Processes*-Modells attraktiver erscheinen, da beide Effekte durch denselben Mechanismus erklärt werden können. Die Notwendigkeit, zwei verschiedene Prozesse zur Erklärung des *Changing-State*- und des Devianz-Effektes heranzuziehen, wird jedoch mit Befunden gerechtfertigt, die für eine funktionale Verschiedenheit des *Changing-State*- und des Devianz-Effektes sprechen (Hughes, Hurlstone, Marsh, Vachon, & Jones, 2013; Hughes et al., 2005, 2007; Sörqvist, 2010; für einen Überblick siehe Hughes, 2014) und daher von zentraler Wichtigkeit für den Gültigkeitsanspruch des Duplex-Modells gegenüber sparsameren Modellen wie dem *Embedded-Processes*-Modell sind.

Als eine der wichtigsten vom Duplex-Modell postulierten Dissoziationen beider Effekte wird die selektive Interferenz mit Enkodierungs- und Gedächtnisprozessen gesehen (Jones, Hughes, & Macken, 2010). Diese Annahme basiert auf der Beobachtung, dass die Störwirkung von *Changing-State*- im Vergleich zu *Steady-State*-Sequenzen unabhängig davon gezeigt werden konnte, ob diese während der Präsentation der visuellen Zielreize oder innerhalb einer darauffolgenden Retentionsphase präsentiert wurden, während das Auftreten des Devianz-Effektes auf die Präsentationsphase der Zielreize beschränkt war (Hughes et al., 2005). Ebenso wird die negative Korrelation der individuellen Arbeitsgedächtniskapazität mit der Größe des Devianz-Effektes bei ausbleibender Korrelation zwischen der Arbeitsgedächtniskapazität und dem *Changing-State*-Effekt häufig als Argument für eine funktionale Verschiedenheit der beiden Effekte herangezogen (Hughes, 2014; Hughes et al., 2013; Sörqvist, 2010). Weitere Befunde, die als Belege für eine Dissoziation der beiden Effekte diskutiert werden, sind zum Beispiel die Abnahme des Devianz-, nicht aber des *Changing-State*-Effektes über Experimentaldurchgänge hinweg (Sörqvist, 2010) sowie die Modulation der Effekte durch Vorinformationen, die sich nur für den Devianz-Effekt – verkleinerter Devianz-Effekt nach Vorabinformation über die Art von Distraktor im nächsten Experimentaldurchgang – aber nicht für den *Changing-State*-Effekt zeigen ließ (Hughes et al., 2013).

Trotz der auf den ersten Blick überzeugend wirkenden Befundlage gibt es mittlerweile Zweifel an den aufgeführten Ergebnissen und damit an der vom Duplex-Modell postulierten Dissoziation der beiden Phänomene (siehe z.B. Röer, Bell, & Buchner, 2014a, 2015; Röer, Bell, Marsh, & Buchner, 2015). Ein Problem dieser Befunde ist, dass diese häufig auf methodisch problematischen Vergleichen über verschiedene Experimente hinweg basieren, in denen entweder der *Changing-State*- oder der Devianz-Effekt untersucht wurde, und die dadurch teilweise kritische methodische Unterschiede aufweisen. Darüber hinaus wurden häufig sehr kleine Stichproben verwendet und statistische Tests auf Unterschiede zwischen den Effekten nicht berichtet. Solche Experimentaldesigns erschweren den Vergleich der beiden Effekte und sind daher ungeeignet, um Schlussfolgerungen über eine funktionale Verschiedenheit der Effekte zu ziehen (vgl. z.B. Röer et al., 2014a). Ziel der vorliegenden Arbeit war es daher, den *Changing-State*- und den Devianz-Effekt direkt miteinander zu vergleichen und die Grundannahmen des Duplex-Modells exemplarisch anhand zweier prominent postulierter Dissoziationen der beiden Effekte zu testen. Beide Effekte wurden dazu im Rahmen von sieben Experimenten in Bezug auf ihre Beeinträchtigung von Enkodierungs- und Gedächtnisprozessen (Experiment 1a, 1b, 2a und 2b) sowie auf ihren Zusammenhang zur Arbeitsgedächtniskapazität (Experiment 3, 4, 5) geprüft. Diese systematische Untersuchung der Annahmen des Duplex-Modells und die Überprüfung damit assoziierter, zum Teil unzureichend empirisch gesicherter Befunde ist zentral für die Legitimation des Duplex-Modells gegenüber sparsameren Modellen wie dem *Embedded-Processes*-Modell und die zugrunde liegenden kognitiven Prozesse des *Changing-State*- und des Devianz-Effektes.

Beeinträchtigung der Arbeitsgedächtnisleistung durch wechselhafte und deviante Distraktoren – Einfluss des Präsentationszeitpunktes

Die serielle Reproduktion erfordert verschiedene Mechanismen kognitiver Informationsverarbeitung, auf die, in Abhängigkeit der Phase innerhalb der Aufgabe, in unterschiedlichem Maße zurückgegriffen werden muss (Hughes et al., 2005; Macken, Mosdell, & Jones, 1999). Während der Präsentation müssen neue Zielreize kontinuierlich enkodiert werden, während parallel eine immer größer werdende Anzahl bereits enkodierter Zielreize im Arbeitsgedächtnis aufrechterhalten werden muss. Zu Beginn der Präsentation ist die Arbeitsgedächtnisbelastung durch die Enkodierung der Zielreize hoch, während ihre Aufrechterhaltung noch verhältnismäßig einfach ist, da erst eine geringe Anzahl an Zielreizen aufrechterhalten werden muss. Im Laufe der Präsentationsphase steigt die kognitive Belastung durch die Aufrechterhaltung der Zielreize an, da eine zunehmende Anzahl an Zielreizen im Arbeitsgedächtnis behalten werden muss. Die kognitive Belastung durch Enkodierungsprozesse bleibt dabei konstant, da durchgängig eine gleichbleibende Anzahl an Zielreizen pro Zeiteinheit enkodiert werden muss. In der Retentionsphase erfolgt nur noch die Aufrechterhaltung der Zielreize. Es ist plausibel anzunehmen, dass die Aufgabe in dieser Phase etwas einfacher wird, da die Koordination von Enkodierungs- und Aufrechterhaltungsprozessen entfällt und die Zielreize mit der Zeit stabiler im Gedächtnis repräsentiert sind (Macken et al., 1999).

Das *Embedded-Processes*-Modell (Cowan, 1995) und das Duplex-Modell (Hughes et al., 2007; 2013) beinhalten widersprüchliche Annahmen bezüglich der zugrunde liegenden Prozesse des *Changing-State*- und des Devianz-Effektes und unterscheiden sich damit in ihren Vorhersagen darüber, welche Prozesse – Enkodierung oder Aufrechterhaltung der Zielreize – während der seriellen Reproduktion durch *Changing-State*- und deviante Sequenzen gestört werden. Im *Embedded-Processes*-Modell (Cowan, 1995) wird angenommen, dass die Störwirkung auditiver Distraktoren abhängig vom Ausmaß der Aufmerksamkeitsablenkung durch die Distraktoren und von der für die Hauptaufgabe benötigten Aufmerksamkeitsressourcen ist. Da *Changing-State*- und deviante Sequenzen im Vergleich zu *Steady-State*-Sequenzen (die, bis an sie habituiert wurde, in geringem Maße Aufmerksamkeit auf sich ziehen können) mehr Aufmerksamkeit von der Enkodierung und Aufrechterhaltung der Zielreize abziehen, wird vorhergesagt, dass die Größe des *Changing-State*- und des Devianz-Effektes in dem Maße zunehmen sollte, in dem die Hauptaufgabe Aufmerksamkeitsressourcen für die Enkodierung und Aufrechterhaltung der Zielreize benötigt.

Im Duplex-Modell (Hughes et al., 2007, 2013) wird dagegen postuliert, dass die Aufrechterhaltung der Zielreize automatisch abläuft und keine Aufmerksamkeit benötigt. Die Präsentation von *Changing-State*-Sequenzen stört diesen Prozess, da die Verarbeitung der Reihenfolgeinformation der Distraktorreize mit der Seriation der Zielreize interferiert. Der Devianz-Effekt hingegen wird durch eine Aufmerksamkeitsablenkung erklärt. Da die Aufrechterhaltung der Zielreize nach dem Modell keine Aufmerksamkeit beansprucht, wird angenommen, dass der Devianz-Effekt selektiv die Enkodierung der Zielreize beeinträchtigt während die Aufrechterhaltung unbeeinträchtigt davon bleiben sollte. Da *Steady-State*-Sequenzen aufgrund fehlender Reihenfolgeinformationen zu keiner Störwirkung führen sollten, wird vom Duplex-Modell vorhergesagt, dass die Größe des *Changing-State*-Effektes vom Ausmaß benötigter Aufrechterhaltungsprozesse der Aufgabe abhängen sollte, während die Größe des Devianz-Effektes lediglich das Ausmaß der kognitiven Belastung durch Enkodierungsprozesse widerspiegeln sollte.

Eine Reihe empirischer Befunde scheinen die Hypothesen des Duplex-Modells auf den ersten Blick zu stützen. So konnten Studien zeigen, dass die Beeinträchtigung der seriellen Reproduktion durch *Changing-State*-Sequenzen unabhängig davon ist, ob diese während der Präsentation der Zielreize oder während einer Retentionsphase dargeboten wurden (Buchner, Rothermund, Wentura, & Mehl, 2004; Miles et al., 1991), was darauf hindeutet, dass *Changing-State*-Sequenzen mit der Aufrechterhaltung der Zielreize im Arbeitsgedächtnis interferieren. In einer detaillierten Analyse konnten Macken et al. (1999) folgenden Verlauf zeigen: *Changing-State*-Sequenzen, die vor der Präsentation von Zielreizen abgespielt wurden, führten im Vergleich zu einer Ruhebedingung zu keiner Beeinträchtigung. Eine geringfügige, aber nicht signifikante Störwirkung erzielten die Sequenzen, wenn sie in der ersten Hälfte der Präsentationsphase dargeboten wurden. Die größte Leistungseinbuße im Vergleich zu Ruhe zeigte sich für

Sequenzen, die in der zweiten Hälfte der Präsentationsphase dargeboten wurden. Auch in der Retentionsphase konnte eine signifikante Störwirkung durch die *Changing-State*-Sequenzen beobachtet werden, wobei der Effekt in der ersten Hälfte der Retentionsphase deskriptiv stärker ausgeprägt war als in der zweiten Hälfte. Die Autoren schlussfolgerten, dass *Changing-State*-Sequenzen die serielle Reproduktion in dem Maße beeinträchtigen, in dem zum Zeitpunkt ihrer Präsentation, die Aufrechterhaltung der Zielreize durch serielles Rehearsal zur Gedächtnisbelastung führt. Zu Beginn der Präsentation ist die Gedächtnisbelastung gering und steigt dann mit Zunahme der zu behaltenden Zielreize an. Am Ende der Retentionsphase reduziert sich die Gedächtnisbelastung laut der Autoren dadurch, dass die Zielreize zu diesem Zeitpunkt durch die aktive Aufrechterhaltung bereits stabiler repräsentiert und dadurch resistenter gegenüber Ablenkung sind.

Nach dem Duplex-Modell (Hughes et al., 2007; 2013; Jones et al., 2010) wird für den Devianz-Effekt postuliert, dass deviante Sequenzen nur mit der Enkodierung, nicht aber mit der Aufrechterhaltung der Zielreize interferieren. Diese Schlussfolgerung basiert auf einer Untersuchung von Hughes et al. (2005), in der sich ein signifikanter Devianz-Effekt zeigte, wenn die Präsentation der devianten Sequenzen während der Enkodierung der Zielreize erfolgte (Experiment 1), dieser Effekt jedoch bei der Präsentation des devianten Distraktors in einer auf die Präsentation folgenden Retentionsphase (Experiment 2) ausblieb. Entsprechend wurde geschlussfolgert, dass die Aufmerksamkeitsablenkung nur einen Effekt auf die Enkodierung hat, die selektiv während der Präsentation der Zielreize stattfindet, aber nicht auf die Aufrechterhaltung der Zielreize, die sowohl während der Präsentationsphase als auch in der Retentionsphase abläuft und die gemäß dieses Ansatzes unabhängig von Aufmerksamkeitsressourcen ist.

Ein direkter Vergleich dieser Untersuchung (Hughes et al., 2005) mit den Befunden von Macken et al. (1999) stellt diese Schlussfolgerung allerdings in Frage. In der Untersuchung von Hughes et al. (2005) wurde der deviante Distraktor als zeitliche Verzögerung des fünften aus insgesamt acht Distraktoren einer Sequenz operationalisiert. Wurde diese Sequenz parallel zur Präsentation der Zielreize dargeboten (Experiment 1), erschien der deviante Distraktor in der zweiten Hälfte der Präsentationsphase, einem Intervall, in dem auch Macken et al. (1999) eine deutliche Beeinträchtigung durch *Changing-State*-Sequenzen zeigen konnte. Wurde die komplette Sequenz jedoch innerhalb einer acht Sekunden langen Retentionsphase präsentiert (Experiment 2), erschien der deviante Distraktor in der zweiten Hälfte der Retentionsphase und damit zu einem Zeitpunkt, in dem auch die von Macken et al. (1999) dargebotenen *Changing-State*-Sequenzen nur noch zu einer geringen Störwirkung führten. Darüber hinaus basierte der relevante Vergleich auf einem Vergleich über Experimente hinweg, in denen das Präsentationsintervall der Distraktoren (Enkodierung versus Retention) mit dem Vorhandensein einer Retentionsphase konfundiert war (Hughes et al., 2005), während sich das Ausbleiben eines Devianz-Effektes in der Retentionsphase in einer aktuelleren Untersuchung ohne eine solche Konfundierung nicht replizieren ließ (Röer, Bell, & Buchner, 2014b).

Die im Duplex-Modell vorgenommene Interpretation der Befunde als klare Dissoziation des *Changing-State*- und des Devianz-Effektes in Form selektiver Interferenz mit Enkodierungs- und Gedächtnisprozessen kann daher angezweifelt werden und macht eine Überprüfung dieser Hypothese notwendig. In den Experimenten 1a - 2b der vorliegenden Arbeit wurde aus diesem Grund auf systematische Weise untersucht, welche Zeitintervalle und damit welche kognitiven Prozesse innerhalb der seriellen Reproduktion am anfälligsten für die Störwirkung von *Changing-State*- (Experiment 1a und Experiment 1b) und devianten Sequenzen (Experiment 2a und Experiment 2b) sind.

Experiment 1a

In Experiment 1a wurde untersucht, welche Zeitintervalle innerhalb der seriellen Reproduktionsaufgabe am anfälligsten für den *Changing-State*-Effekt (den Unterschied in der Leistung zwischen einer *Steady-State*- und einer *Changing-State*-Bedingung) sind. Dies ist von besonderer Bedeutung, da die Untersuchung von Macken et al. (1999) auf einem Vergleich der Störwirkung von *Changing-State*-Sequenzen mit einer Ruhe-Bedingung basiert und daher nicht die Schlussfolgerung rechtfertigt, dass der beobachtete Effekt spezifisch für die Interferenz von *Changing-State*-Sequenzen mit der Aufrechterhaltung der Zielreize ist. Ebenso denkbar ist es, dass der gefundene Verlauf auf eine allgemeine Störwirkung auditiver Distraktoren bei hoher Arbeitsgedächtnisbelastung zurückzuführen ist. In Experiment 1a wurde aus diesem Grund dasselbe Design wie bei Macken et al. (1999) verwendet, wobei sowohl *Changing-State*- als auch *Steady-State*-Sequenzen in der ersten Hälfte der Präsentationsphase (Enkodierung 1), in der zweiten Hälfte der Präsentationsphase (Enkodierung 2), in der ersten Hälfte der Retentionsphase (Retention 1) und in der zweiten Hälfte der Retentionsphase (Retention 2) präsentiert wurden[1].

Das Duplex-Modell (Hughes et al., 2007; 2013; Jones et al., 2010) sagt vorher, dass der *Changing-State*-Effekt am geringsten ausgeprägt sein sollte, wenn die Distraktorsequenzen in Enkodierung 1 präsentiert werden, da zu diesem Zeitpunkt erst eine kleine Anzahl an Zielreizen (bis maximal vier) durch serielles Rehearsal im Gedächtnis aufrecht erhalten werden müssen. Der größte Effekt sollte sich bei der Darbietung von Distraktoren in Enkodierung 2 und in Retention 1 zeigen, da innerhalb dieser Phasen die kognitive Belastung durch die Aufrechterhaltung der Zielreize am höchsten ist. Es ist vorstellbar, dass die Größe des Effektes in Retention 2 wieder abnimmt, da die Zielreize aufgrund des kontinuierlichen Rehearsals zu diesem Zeitpunkt bereits stabiler im Gedächtnis repräsentiert sind (Macken et al., 1999). Da *Steady-State*-Sequenzen keine Reihenfolgeinformation enthalten und daher nicht mit der Aufrechterhaltung der Zielreize interferieren, sollte die Leistung in der *Steady-State*-Bedingung unabhängig vom Präsentationszeitpunkt sein.

Im Gegensatz dazu nimmt das *Embedded-Processes*-Modell (Cowan, 1995) an, dass das Ausmaß der Störwirkung davon abhängig ist, wie viel Aufmerksamkeit die Distraktoren auf sich ziehen und wie viel Aufmerksamkeit für die Aufgabe benötigt wird. *Changing-State*-Sequenzen sollten mehr Aufmerksamkeit auf sich ziehen als *Steady-State*-Sequenzen, aber auch das Einsetzen von *Steady-State*-Sequenzen kann ein gewisses Maß an Aufmerksamkeit auf sich ziehen, bis das kognitive System an die wiederholte Präsentation der einzelnen Distraktoren innerhalb der Sequenzen habituiert. Die serielle Reproduktionsaufgabe sollte zu Beginn noch relativ einfach sein, solange die Anzahl der zu erinnernden Reize geringer ist als die Anzahl an Reizen, die parallel im Fokus der Aufmerksamkeit behalten werden kann (kleiner als vier, Co-

[1] In der Untersuchung von Macken et al. (1999) wurden auch Distraktoren vor der Präsentation der Zielreize abgespielt. Die Präsentation der Reize zu diesem Zeitpunkt hatte jedoch keinen Einfluss auf die serielle Reproduktionsleistung. Da dieser Befund durch alle hier getesteten Modelle so vorhergesagt wird und dadurch keinen Informationsgewinn verspricht, wurde dieses Präsentationsintervall in den vorliegenden Experimenten nicht umgesetzt.

wan, 2001). Die Arbeitsgedächtnisbelastung sollte jedoch drastisch zunehmen, wenn eine größere Anzahl an Zielreizen durch kontinuierliche Reaktivierung im Fokus der Aufmerksamkeit aufrecht erhalten werden muss und parallel neue Reize in die Sequenz zu erinnernder Reize integriert werden müssen. Das Modell sagt daher einen u-förmigen Verlauf der Leistung vorher. Die Leistung sollte besser sein, wenn die Distraktorsequenzen in Enkodierung 1 im Vergleich zu Enkodierung 2 präsentiert werden. Bei Distraktoren in Retention 1 sollte sich ebenfalls eine reduzierte Leistung zeigen, die sich möglicherweise in Retention 2 etwas verbessert, wenn die Zielreize durch ihre kontinuierliche Reaktivierung stabiler im Gedächtnis repräsentiert sind. Entscheidend ist, dass sich dieser Verlauf in beiden Distraktorbedingungen zeigen sollte, wobei er jedoch in der *Changing-State*-Bedingung stärker ausgeprägt sein sollte als in der *Steady-State*-Bedingung, da *Steady-State*-Distraktoren weniger Aufmerksamkeit auf sich ziehen.

Die visuellen Zielreize der seriellen Reproduktionsaufgabe bestanden aus acht Ziffern, die zufällig, ohne Zurücklegen, aus dem Zahlenraum von eins bis neun gezogen und nacheinander (800 ms Präsentation, 200 ms Interstimulusintervall) auf einem Bildschirm präsentiert wurden. Die auditiven Distraktorsequenzen wurden über Kopfhörer präsentiert und bestanden aus acht, von einer männlichen Stimme gesprochenen, einsilbigen deutschen Wörtern (Alm, Elch, Gel, Jod, Milz, Schopf, Streu, Tau). Für die *Changing-State*-Sequenzen wurden diese nacheinander in zufälliger Reihenfolge präsentiert. Für die *Steady-State*-Sequenzen wurde jeweils eines der Wörter achtmal hintereinander dargeboten, wobei jedes Wort viermal als *Steady-State*-Sequenz im Experiment verwendet wurde. Jeder Experimentaldurchgang startete mit einer 8-sekündigen Präsentation der Zielreize, die dann innerhalb einer 8-sekündigen Retentionsphase aufrecht erhalten werden sollten. Auf die Retentionsphase folgte die Abrufphase, in der die Teilnehmerinnen und Teilnehmer die Zielreize in ihrer Präsentationsreihenfolge über die Computertastatur eingeben sollten. Innerhalb der 32 *Changing-State*- und 32 *Steady-State*-Durchgänge wurden die Distraktorsequenzen jeweils achtmal während einem der vier Präsentationsintervalle gespielt (Enkodierung 1, Enkodierung 2, Retention 1, Retention 2). Die Reihenfolge der Durchgänge war randomisiert (für eine schematische Darstellung des Experimentalablaufes siehe Abbildung 1 in Körner, Röer, Buchner und Bell, 2017a).

Die Ergebnisse zeigten, dass die serielle Reproduktionsleistung (Anteil an korrekt erinnerten Zielreizen im Hinblick auf ihre Identität und Position innerhalb der Zielreizsequenz) stärker durch die *Changing-State-* als durch die *Steady-State*-Distraktoren beeinträchtigt war [$F(1,89) = 35.23$, $p < .001$, $\eta_p^2 = .28$]. Der signifikante Haupteffekt des Präsentationszeitpunktes [$F(3,87) = 22.16$, $p < .001$, $\eta_p^2 = .43$] spiegelte sich in einem u-förmigen Verlauf der seriellen Reproduktionsleistung über die Zeitpunkte wider. Die Interaktion zwischen Distraktorbedingung und Präsentationszeitpunkt wurde knapp nicht signifikant [$F(3,87) = 2.52$, $p = .06$, $\eta_p^2 = .08$]. Es gab einen signifikanten *Changing-State*-Effekt bei der Darbietung der Distraktoren zu allen vier Präsentationszeitpunkten [Enkodierung 1, $F(1,89) = 8.66$, $p < .01$, $\eta_p^2 = .09$; Enkodierung 2, $F(1,89) = 24.90$, $p < .001$, $\eta_p^2 = .22$; Retention 1, $F(1,89) = 4.21$, $p = .04$, $\eta_p^2 = .05$; Retention 2, $F(1,89) = 4.26$, $p = .04$, $\eta_p^2 = .05$], der deskriptiv am deutlichsten in Enkodierung 2 ausgeprägt war (für die deskriptiven Ergebnisse siehe Tabelle 1 in Körner et al., 2017a).

Der Verlauf der *Changing-State*-Bedingung entspricht den Befunden von Macken et al. (1999) und den Vorhersagen des Duplex-Modells (Hughes et al., 2007; 2013; Jones et al., 2010). Die geringste Störwirkung zeigte sich, wenn die Distraktoren in Enkodierung 1 präsentiert wurden, einem Zeitpunkt zu dem erst eine geringe Anzahl an Zielreizen aufrechterhalten werden musste. Bei hoher kognitiver Belastung durch die Aufrechterhaltung der Zielreize, wenn die Distraktoren in Enkodierung 2 und Retention 1 dargeboten wurden, war die Störwirkung am ausgeprägtesten. Nach dem Duplex-Modell sollte sich dieser Verlauf spezifisch für den *Changing-State*-Effekt zeigen, das bedeutet, er sollte allein auf die zeitpunktabhängige Beeinträchtigung der seriellen Reproduktion durch *Changing-State*-Sequenzen zurückzuführen sein. Die Leistung in der *Steady-State*-Bedingung sollte dagegen unabhängig vom Präsentationszeitpunkt sein, da *Steady-State*-Sequenzen keine Reihenfolgeinformation beinhalten und daher nicht mit dem für die Aufrechterhaltung der Zielreize notwendigen Seriationsprozess interferieren sollten. Der Haupteffekt der Distraktorbedingung bei gleichzeitigem Ausbleiben einer signifikanten Interaktion zwischen Distraktorbedingung und Präsentationszeitpunkt widerspricht jedoch dieser Annahme und deutet eher auf eine generell erhöhte Sensitivität für auditive Ablenkung bei hoher Arbeitsgedächtnisbelastung hin, was eher im Einklang mit den Annahmen des *Embedded-Processes*-Modells steht. Die Ergebnisse aus Experiment 1a sprechen also dafür, dass die Befunde von Macken et al. (1999) nicht spezifisch für *Changing-State*-Distraktoren sind, sondern eher eine allgemeine, zeitpunktabhängige Sensitivität für auditive Ablenkung widerspiegeln. Da die Interaktion zwischen Distraktorbedingung und Präsentationszeitpunkt allerdings nur knapp nicht signifikant wurde und sich deskriptiv die größte Differenz der Leistung zwischen *Steady-State*- und *Changing-State*-Bedingung in Enkodierung 2 zeigte, ist die Schlussfolgerung, dass die Größe des *Changing-State*-Effektes unabhängig vom Präsentationszeitpunkt ist, möglicherweise voreilig. Um die Befunde auf eine breitere empirische Basis zu stellen, wurden in Experiment 1b mehr Daten erhoben und dieses als konzeptuelle Replikation von Experiment 1a durchgeführt.

Experiment 1b

In Experiment 1b wurde, wie in der Originalstudie von Macken et al. (1999), natürliche Sprache als *Changing-State*-Sequenzen verwendet, da sie im Vergleich zu Sequenzen bestehend aus einsilbigen Wörtern mehr akustische Variabilität aufweist – eine Hauptdeterminante auditiver Ablenkung (Tremblay, Nicholls, Alford, & Jones, 2000) – und entsprechend zu größerer Störwirkung führen kann (Röer, Bell, & Buchner, 2015). Im Vergleich zu Experiment 1a wurde in Experiment 1b ein größerer *Changing-State*-Effekt erwartet, was die Wahrscheinlichkeit erhöhen sollte, eine Modulation des Effektes durch den Präsentationszeitpunkt zu finden.

Die Methode von Experiment 1b war identisch zu Experiment 1a bis auf die Tatsache, dass 32 Sätze (im Vergleich zu Sequenzen aus einsilbigen Wörtern) als *Changing-State*-Sequenzen verwendet wurden. Für die 32 *Steady-State*-Sequenzen wurde aus jedem Satz ein einsilbiges Wort ausgewählt und dabei die Anzahl an Wiederholungen dieses Wortes an die Wortanzahl der *Changing-State*-Sequenzen angepasst.

Wie in Experiment 1a waren die Teilnehmerinnen und Teilnehmer in Experiment 1b stärker durch die *Changing-State*- als durch die *Steady-State*-Sequenzen in ihrer Reproduktionsleistung beeinträchtigt [$F(1,78) = 51.09$, $p < .001$, $\eta_p^2 = .40$]. Dieser Effekt war größer als in Experiment 1a ($\eta_p^2 = .28$). Zudem variierte die Leistung über die Präsentationszeitpunkte [$F(3,76) = 31.96$, $p < .001$, $\eta_p^2 = .56$]. Die signifikante Interaktion zwischen der Distraktorbedingung und dem Präsentationszeitpunkt [$F(3,76) = 5.05$, $p < .01$, $\eta_p^2 = .17$] spiegelte die Tatsache wider, dass auch die Größe des *Changing-State*-Effektes in Abhängigkeit des Präsentationszeitpunktes variierte und bei der Darbietung der Distraktoren in Enkodierung 1 nicht signifikant wurde [$F(1,78) = 1.44$, $p = .23$, $\eta_p^2 = .02$], am größten war, wenn die Distraktoren in Enkodierung 2 [$F(1,78) = 20.35$, $p < .001$, $\eta_p^2 = .21$] und Retention 1 [$F(1,78) = 42.59$, $p < .001$, $\eta_p^2 = .35$] dargeboten wurden und bei der Darbietung der Distraktoren in Retention 2 [$F(1,78) = 11.53$, $p < .001$, $\eta_p^2 = .13$] wieder abnahm (für die deskriptiven Ergebnisse siehe Tabelle 1 in Körner et al., 2017a).

Dies stützt die Annahme von Macken et al. (1999), dass die Größe des *Changing-State*-Effektes mit der Gedächtnisbelastung durch die Aufrechterhaltung der Zielreize ansteigt. Im Vergleich zur Untersuchung von Macken et al (1999), in der keine *Steady-State*-Kontrollbedingung verwendet wurde und mit der diese Fragestellung daher nicht direkt untersucht werden konnte, bietet Experiment 1b daher erste empirische Evidenz für die Abhängigkeit der Größe des *Changing-State*-Effektes vom Präsentationszeitpunkt und damit der Gedächtnisbelastung während der seriellen Reproduktion.

Kombinierte Analyse der Experimente 1a und 1b

Um die statistische Teststärke der Experimente zu erhöhen, wurden die Daten aus Experiment 1a und 1b kombiniert. Mit einer Stichprobengröße von $N = 169$ zeigte sich ein klassischer *Changing-State*-Effekt [$F(1,167) = 87.08$, $p < .001$, $\eta_p^2 = .34$] sowie ein Effekt des Präsentationszeitpunktes [$F(3,165) = 51.36$, $p < .001$, $\eta_p^2 = .48$]. Die Leistung unterschied sich nicht zwischen den Experimenten [$F(1,167) = 0.45$, $p = .50$, $\eta_p^2 < .01$] und es gab keine signifikante Interaktion zwischen dem Faktor Experiment und der Distraktorbedingung [$F(1,167) = 2.22$, $p = .14$, $\eta_p^2 = .01$] oder dem Präsentationszeitpunkt [$F(3,165) = 1.75$, $p = .16$, $\eta_p^2 = .03$]. Die Größe des *Changing-State*-Effektes variierte in Abhängigkeit des Präsentationszeitpunktes [$F(3,165) = 3.16$, $p = .03$, $\eta_p^2 = .05$]. Der *Changing-State*-Effekt war am kleinsten, wenn die Distraktorsequenzen in Enkodierung 1 präsentiert wurden [$F(1,168) = 9.47$, $p < .01$, $\eta_p^2 = .05$]. Der größte Effekt zeigte sich, wenn die Distraktorsequenzen in Enkodierung 2 präsentiert wurden [$F(1,168)$

= 45.02, $p < .001$, $\eta_p^2 = .21$]. Auch in Retention 1 zeigte sich noch ein deutlicher *Changing-State*-Effekt [$F(1,168) = 31.65$, $p < .001$, $\eta_p^2 = .16$], der in Retention 2 immer noch signifikant, aber in seiner Größe reduziert war [$F(1,168) = 14.95$, $p < .001$, $\eta_p^2 = .08$]. Ebenfalls zeigte sich eine signifikante Dreifachinteraktion zwischen den Faktoren Distraktorbedingung, Präsentationszeitpunkt und Experiment [$F(3,165) = 3.72$, $p = .03$, $\eta_p^2 = .05$], die auf die Tatsache zurückgeführt werden kann, dass die Interaktion zwischen der Distraktorbedingung und dem Präsentationszeitpunkt in Experiment 1a knapp nicht signifikant wurde ($p = .06$) aber in Experiment 1b signifikant war ($p < .01$, für die deskriptiven Ergebnisse siehe Abbildung 2 in Körner et al., 2017a).

Die Tatsache, dass die Größe des *Changing-State*-Effektes mit der Gedächtnisbelastung durch die Aufrechterhaltung der Zielreize anstieg, entspricht den Vorhersagen des Duplex-Modells. Allerdings scheint dieses Befundmuster nicht spezifisch für *Changing-State*-Sequenzen zu sein, da sich dieser Verlauf der Leistung über die Präsentationszeitpunkte sowohl in der *Steady-State*- [$F(3,166) = 9.69$, $p < .001$, $\eta_p^2 = .15$] als auch in der *Changing-State*-Bedingung [$F(3,166) = 35.58$, $p < .001$, $\eta_p^2 = .39$] zeigte. Dies widerspricht den Annahmen des Duplex-Modells, laut dem sich dieser Effekt selektiv für die *Changing-State*- und nicht für die *Steady-State*-Bedingung zeigen sollte, die keine Reihenfolgeinformation beinhaltet und daher nicht mit der Seriation zur Aufrechterhaltung der Zielreize interferieren sollte. Experiment 2a und 2b dienen der Prüfung, ob sich dieses Befundmuster auch auf eine weitere Art auditiver Ablenkung, den Devianz-Effekt, das heißt die Beeinträchtigung der seriellen Reproduktion durch deviante im Vergleich zu Steady-State-Sequenzen, übertragen lässt.

Experiment 2a

In Experiment 2a wurden deviante Sequenzen in denselben vier Präsentationsintervallen wie in den vorangegangenen Experimenten dargeboten. Laut dem Duplex-Modell (Hughes et al., 2007; 2013; Jones et al., 2010) interferiert die Aufmerksamkeitsablenkung durch deviante Distraktoren selektiv mit der Enkodierung der Zielreize, während deren Aufrechterhaltung unbeeinträchtigt durch Aufmerksamkeitsprozesse sein sollte. Entsprechend sagt das Modell vorher, dass deviante Sequenzen nur zur Beeinträchtigung der seriellen Reproduktionsleistung führen sollten, wenn diese in Enkodierung 1 oder Enkodierung 2, nicht aber in Retention 1 und Retention 2 dargeboten werden. Das *Embedded-Processes*-Modell (Cowan, 1995) nimmt dagegen an, dass der *Changing-State*- und der Devianz-Effekt auf Aufmerksamkeitsablenkung beruhen, welche sowohl die Enkodierung als auch die Aufrechterhaltung der Zielreize beeinträchtigt. Dieses Modell sagt daher vorher, dass die Ergebnisse von Experiment 2a denen von Experiment 1a und 1b ähneln sollten. Der Devianz-Effekt sollte am geringsten sein, wenn die Distraktorsequenzen in Enkodierung 1 präsentiert werden und am stärksten ausgeprägt sein, wenn diese in Enkodierung 2 präsentiert werden. Im Gegensatz zu den Vorhersagen des Duplex-Modells sollte sich jedoch auch ein Devianz-Effekt zeigen, wenn die Distraktoren in Retention 1 und Retention 2 dargeboten werden.

Die Methode von Experiment 2a war identisch zu Experiment 1a und Experiment 1b, bis auf die Tatsache, dass 32 verschiedene deviante Sequenzen und 32 *Steady-State*-Sequenzen als Distraktoren verwendet wurden, die aus den, bereits in Experiment 1a verwendeten acht einsilbigen deutschen Substantiven bestanden. In der Devianz-Bedingung wurde die mehrfache Wiederholung desselben Wortes durch ein einzelnes abweichendes Wort – dem auditiven Deviant – unterbrochen. In jedem der 32 Durchgänge der Devianz-Bedingung wurde der auditive Deviant an einer von acht möglichen Positionen innerhalb von Enkodierung 1, Enkodierung 2, Retention 1 oder Retention 2 dargeboten, wobei der Deviant während des Experimentes nur einmal an jeder der insgesamt 32 möglichen Positionen erschien. Jeder Durchgang begann mit einer 15.5 Sekunden langen Vorphase. Der Beginn der Präsentation der *Steady-State*-Sequenzen variierte in Abhängigkeit der Position des auditiven Deviants, um sicherzustellen, dass dieser unabhängig von seiner Position nach genau 31 *Steady-State*-Wortwiederholungen dargeboten wurde (für eine schematische Darstellung des Experimentalablaufes siehe Abbildung 3 in Körner et al., 2017a). Dieses Vorgehen sollte sicherstellen, dass die Teilnehmerinnen und Teilnehmer gleich viel Zeit für den Aufbau eines neuronalen Modells der vorangegangenen *Steady-State*-Stimulation hatten, unabhängig davon, an welcher Position der deviante Stimulus präsentiert wurde. Um eine Konfundierung des Präsentationszeitpunktes des auditiven Deviants mit der Gesamtdauer der Darbietung auditiver Distraktoren während der Präsentation der Zielreize und der Retentionsphase zu verhindern, wurden die *Steady-State*-

Distraktoren durchgängig während der Präsentations- und der Retentionsphase dargeboten. Jede Sequenz der Devianz-Bedingung entsprach in ihrer Länge und ihrem Präsentationsbeginn in der Vorphase einer *Steady-State*-Sequenz, bis auf die Tatsache, dass kein deviantes Wort in der Sequenz präsentiert wurde. Jedes Distraktorwort wurde viermal als *Steady-State*-Wortwiederholung in jeder Distraktorbedingung dargeboten. In der Devianz-Bedingung wurde für jeden Durchgang ein anderes, randomisiert gezogenes Wort als devianter Stimulus verwendet.

Die serielle Reproduktionsleistung war in der Devianz-Bedingung schlechter als in der *Steady-State*-Bedingung [$F(1,101) = 12.23$, $p < .01$, $\eta_p^2 = .11$] und variierte in Abhängigkeit des Präsentationszeitpunktes [$F(3,99) = 3.76$, $p = .01$, $\eta_p^2 = .10$]. Wie in Experiment 1a wurde die Interaktion zwischen Distraktorbedingung und Präsentationszeitpunkt knapp nicht signifikant [$F(3,99) = 2.58$, $p = .06$, $\eta_p^2 = .07$], was den Annahmen des Duplex-Modells (Hughes et al., 2007; 2013; Jones et al., 2010) widerspricht, dass sich der Devianz-Effekt nur bei einer Präsentation des devianten Distraktors in der Enkodierung zeigen sollte. Jedoch war die Störwirkung wie in den vorangegangenen Experimenten am größten, wenn der deviante Distraktor in Enkodierung 2 [$F(1,101) = 7.44$, $p < .01$, $\eta_p^2 = .07$] und Retention 1 [$F(1,101) = 11.38$, $p < .01$, $\eta_p^2 = .10$] dargeboten wurde, während sich kein signifikanter Effekt in Enkodierung 1 [$F(1,101) = .16$, $p = .69$, $\eta_p^2 < .01$] und Retention 2 [$F(1,101) = .74$, $p = .39$, $\eta_p^2 < .01$] zeigte (für die deskriptiven Ergebnisse siehe Tabelle 1 in Körner et al., 2017a). Es scheint daher voreilig zu schlussfolgern, dass der Devianz-Effekt unabhängig vom Präsentationszeitpunkt ist. Analog zum Vorgehen in Experiment 1a und 1b wurde die Abhängigkeit des Devianz-Effektes vom Präsentationszeitpunkt einem Test mit größerer statistischer Power unterzogen, indem in Experiment 2b, als konzeptuelle Replikation von Experiment 2a, zusätzliche Daten erhoben und diese anschließend mit den Daten aus Experiment 2a kombiniert wurden.

Experiment 2b

Es wird davon ausgegangen, dass der Devianz-Effekt auf einer Erwartungsverletzung der vorangegangenen regelhaften akustischen Stimulation durch die devianten Distraktoren basiert (Nöstl, Marsh, & Sörqvist, 2012, 2014; Röer et al., 2014b; Vachon et al., 2012). In Experiment 2a wurden in der Hälfte aller Durchgänge deviante Reize präsentiert, sodass es vorstellbar ist, dass dieser hohe Anteil an Devianz-Durchgängen das globale Ausmaß der Erwartungsverletzung (über das ganze Experiment hinweg) reduzierte und daher zu einer geringeren Störwirkung in der Devianz-Bedingung führte. In Experiment 2b wurden aus diesem Grund die Anzahl an Devianz-Durchgängen und damit ihre Vorhersehbarkeit reduziert. Im Vergleich zu Experiment 2a wurde daher ein größerer Devianz-Effekt erwartet und damit eine erhöhte Wahrscheinlichkeit, eine Interaktion zwischen Distraktorbedingung und dem Präsentationszeitpunkt zu finden.

Die Methode von Experiment 2b entsprach der Methode von Experiment 2a abgesehen davon, dass lediglich 16 Durchgänge in der Devianz-Bedingung mit 48 Durchgängen in der *Steady-State*-Bedingung verglichen wurden. Aufgrund dieses Designs wurden die devianten Distraktoren jeweils an einer von vier möglichen Positionen (Position 3, 4, 5 oder 6) innerhalb von Enkodierung 1, Enkodierung 2, Retention 1 und Retention 2 präsentiert. Jeder Durchgang startete mit einer 13.5 Sekunden langen Vorphase, in der keine Zielreize präsentiert wurden. Unabhängig von der Position des devianten Distraktors wurden jeweils 29 *Steady-State*-Distraktoren vor jedem devianten Distraktor präsentiert. Jede Sequenz der Devianz-Bedingung entsprach in ihrer Länge und ihrem Präsentationsbeginn in der Vorphase drei *Steady-State*-Sequenzen.

Die serielle Reproduktionsleistung war in der Devianz-Bedingung schlechter als in der *Steady-State*-Bedingung [$F(1,122) = 29.08$, $p < .001$, $\eta_p^2 = .19$], variierte aber nicht in Abhängigkeit des Präsentationszeitpunktes [$F(3,120) = 1.77$, $p = .16$, $\eta_p^2 = .04$]. Allerdings zeigte sich eine signifikante Interaktion zwischen Distraktorbedingung und Präsentationszeitpunkt [$F(3,120) = 3.77$, $p = .01$, $\eta_p^2 = .09$]. Wurden der deviante Distraktor in Enkodierung 1 gespielt, zeigte sich ein kleiner Devianz-Effekt [$F(1,122) = 5.13$, $p = .03$, $\eta_p^2 = .04$]. Die Präsentation des devianten Distraktors in Enkodierung 2 erzielte den größten Devianz-Effekt [$F(1,122) = 27.42$, $p < .001$, $\eta_p^2 = .18$]. Bei der Präsentation des devianten Distraktors in Retention 1 zeigte sich kein Devianz-Effekt [$F(1,122) = 0.35$, $p = .56$, $\eta_p^2 < .01$], allerdings konnte in Retention 2 ein kleiner, aber signifikanter Devianz-Effekt beobachtet werden [$F(1,122) = 6.48$, $p = .01$, $\eta_p^2 = .05$; für die deskriptiven Ergebnisse siehe Tabelle 1 in Körner et al., 2017].

Die Tatsache, dass sich mit der reduzierten Anzahl an Devianz-Durchgängen in Experiment 2b im Vergleich zu Experiment 2a ein größerer Devianz-Effekt zeigte, entspricht Befunden, die zeigen, dass Aufmerksamkeitsablenkung nicht nur durch Erwartungsverletzung auf lokalem Niveau (innerhalb eines einzelnen Durchgangs; Röer et al., 2014b), sondern auch auf globalem Niveau (über Experimentaldurchgänge hinweg; Röer et al., 2011; Vachon et al., 2012) determiniert ist. Abgesehen davon ähnelte das Befundmuster den vorangegangen Experimenten, in denen ebenfalls Enkodierung 2 am anfälligsten für die Störwirkung devianter Sequenzen war.

Kombinierte Analyse der Experimente 2a und 2b

Analog zu Experiment 1a und 1b wurden die Daten von Experiment 2a und 2b kombiniert, wodurch sich eine Stichprobengröße von N = 225 ergab. Die kombinierten Daten zeigten, dass die Leistung in der Devianz-Bedingung schlechter war als in der *Steady-State*-Bedingung [$F(1,223) = 38.63$, $p < .001$, $\eta_p^2 = .15$] und in Abhängigkeit des Präsentationszeitpunktes variierte [$F(3,221) = 4.61$, $p < .01$, $\eta_p^2 = .06$]. Die Leistung unterschied sich nicht zwischen den Experimenten [$F(1,223) = 0.12$, $p = .74$, $\eta_p^2 < .01$] und es gab keine signifikante Interaktion zwischen dem Faktor Experiment und der Distraktorbedingung [$F(1,223) = 1.08$, $p = .30$, $\eta_p^2 < .01$] oder dem Präsentationszeitpunkt [$F(3,221) = 1.04$, $p = .38$, $\eta_p^2 = .01$]. Zudem bestätigte die signifikante Interaktion zwischen Präsentationszeitpunkt und Distraktorbedingung [$F(3,221) = 2.95$, $p = .03$, $\eta_p^2 = .04$], dass auch der Devianz-Effekt in Abhängigkeit des Präsentationszeitpunktes variiert. Der kleinste Devianz-Effekt zeigte sich bei der Präsentation des devianten Distraktors in Enkodierung 1 [$F(1,224) = 4.32$, $p = .04$, $\eta_p^2 = .02$]; der größte Effekt zeigte sich, wenn der deviante Distraktor in Enkodierung 2 präsentiert wurde [$F(1,224) = 31.92$, $p < .001$, $\eta_p^2 = .12$]. Auch die Präsentation des devianten Distraktors in Retention 1 [$F(1,224) = 6.25$, $p = .01$, $\eta_p^2 = .03$] und Retention 2 [$F(1,224) = 6.41$, $p = .01$, $\eta_p^2 = .03$] führte zu einem signifikanten Devianz-Effekt. Ebenfalls zeigte sich eine signifikante Dreifachinteraktion zwischen den Faktoren Distraktorbedingung, Präsentationszeitpunkt und Experiment [$F(3,221) = 2.66$, $p = .05$, $\eta_p^2 = .04$], die auf die Tatsache zurückgeführt werden kann, dass die Interaktion zwischen der

Distraktorbedingung und dem Präsentationszeitpunkt in Experiment 2a knapp nicht signifikant wurde (p = .06), aber in Experiment 2b signifikant war (p = .01, für die deskriptiven Ergebnisse siehe Abbildung 4 in Körner et al., 2017a). Dieses Befundmuster gleicht dem aus Experiment 1a und 1b und deutet darauf hin, dass sich der Devianz-Effekt qualitativ nicht vom *Changing-State*-Effekt unterscheidet.

Diskussion der Experimente 1a, 1b, 2a und 2b

Zusammengefasst zeigen die Befunde aus Experiment 1a, 1b, 2a und 2b, dass sowohl der *Changing-State*- als auch der Devianz-Effekt in Abhängigkeit des Präsentationszeitpunktes variieren. Anders als vom Duplex-Modell vorhergesagt, spiegelte sich diese Interaktion der Distraktorbedingung und des Präsentationszeitpunktes im selben Verlauf für *Changing-State*- und deviante Sequenzen wider, deren Präsentation sowohl während der Präsentation der Zielreize als auch in der Retentionsphase zu einer Leistungsbeeinträchtigung führte. Dies spricht klar gegen eine funktionale Verschiedenheit der Effekte und deutet daraufhin, dass nicht nur *Changing-State*- sondern auch deviante Sequenzen mit der Aufrechterhaltung der Zielreize interferieren.

Dennoch passt das Befundmuster nicht zur Annahme, dass die Größe der Störwirkung eine lineare Funktion der kognitiven Beanspruchung allein durch die Aufrechterhaltung der Zielreize ist (Macken et al., 1999). Gemäß dieser Erklärung sollte die Präsentation von Distraktoren in Retention 1 den größten Störeffekt erzielen, wenn bereits alle acht Zielreize präsentiert wurden und aufrechterhalten werden müssen. Die vorliegenden Befunde zeigen jedoch, dass Enkodierung 2, wenn vier bis acht Reize aufrecht erhalten werden und parallel weitere Zielreize enkodiert werden müssen, am anfälligsten für die Störwirkung auditiver Distraktoren war. Die Ergebnisse passen daher besser zu der Annahme, dass nicht selektiv die Enkodierung oder die Aufrechterhaltung der Reize gestört wird, sondern dass die Größe der Störwirkung auditiver Distraktoren (unabhängig von der Art der Distraktoren) mit der allgemeinen kognitiven Beanspruchung ansteigt, die sowohl für die Enkodierung als auch die Aufrechterhaltung von Zielreizen und die Koordination beider kognitiver Prozesse benötigt wird. Diese Erklärung und die

Ergebnisse der Experimente 1a bis 2b passen daher besser zu den Annahmen des *Embedded-Processes*-Modell, laut dem die Störwirkung unabhängig von der Art der Distraktoren umso größer sein sollte, je mehr Aufmerksamkeitsressourcen sowohl für die Enkodierung als auch die Aufrechterhaltung der Zielreize benötigt wird und je mehr Aufmerksamkeit die Distraktoren von diesen Prozessen abziehen.

Beeinträchtigung der Arbeitsgedächtnisleistung durch wechselhafte und deviante Distraktoren – Einfluss der Arbeitsgedächtniskapazität

In den ersten vier Experimenten der vorliegenden Arbeit zeigte sich, dass die Störwirkung von *Changing-State*- und devianten Distraktoren abhängig von ihrem Präsentationszeitpunkt und damit von den zu diesem Zeitpunkt ablaufenden kognitiven Prozessen ist, sich aber qualitativ nicht in Abhängigkeit der Art der Distraktoren unterschied. Die Störwirkung der auditiven Distraktoren war dann am stärksten ausgeprägt, wenn diese zu einem Zeitpunkt präsentiert wurden, zu dem die Arbeitsgedächtnisbelastung besonders hoch ist, was dafür spricht, dass beide Arten der auditiven Ablenkung mit denselben kognitiven Prozessen im Arbeitsgedächtnis interferieren. Dabei wurden nur die Aufgabenanforderungen betrachtet und individuelle Unterschiede in kognitiven Fähigkeiten nicht berücksichtigt. Geht man davon aus, dass unabhängig von der Art der auditiven Distraktoren dieselben Arbeitsgedächtnisprozesse beeinträchtigt werden, sollten sich individuelle kognitive Fähigkeiten wie die Arbeitsgedächtniskapazität ebenfalls gleichermaßen auf die Größe des *Changing-State*- und des Devianz-Effektes auswirken. Diese Hypothese wurde in Experiment 3, 4 und 5 überprüft, in denen individuelle Unterschiede in der Arbeitsgedächtnisleistung und ihr Zusammenhang zu auditiver Ablenkung durch *Changing-State*- und deviante Distraktoren untersucht wurden.

Basierend auf den unterschiedlichen Annahmen zugrunde liegender Prozesse des *Changing-State*- und des Devianz-Effektes machen das *Embedded-Processes*-Modell (Cowan, 1995) und das Duplex-Modell (Hughes, 2014; Hughes et al., 2013) unterschiedliche Vorhersagen dazu, wie sich die individuelle Arbeitsgedächtniskapazität auf die Größe des *Changing-*

State- und des Devianz-Effektes auswirken sollte. Aus dem *Embedded-Processes*-Modell (Cowan, 1995) lassen sich keine spezifischen Vorhersagen bezüglich der Richtung des Zusammenhangs zwischen der Arbeitsgedächtniskapazität und auditiver Ablenkung ableiten, da diese vom Verständnis davon abhängen, welche konkreten Fähigkeiten individuelle Unterschiede in der Arbeitsgedächtniskapazität abbilden. Auf der einen Seite ist es plausibel anzunehmen, dass hohe Arbeitsgedächtniskapazität – als Fähigkeit, sich stärker auf die Hauptaufgabe zu konzentrieren (Engle, 2002) – zu einer geringeren Ablenkung führen sollte (Elliott, 2002; Elliott & Cowan, 2005; Hughes et al., 2013; Sörqvist, 2010; Sörqvist, Marsh, & Nöstl, 2013). Ein Verständnis von Arbeitsgedächtniskapazität als Fähigkeit, mehr Informationen parallel durch Rehearsal im Arbeitsgedächtnis aufrecht zu erhalten (Unsworth & Engle, 2007), lässt auf der anderen Seite aber auch den gegenteiligen Schluss eines positiven Zusammenhangs zu. Da auditive Distraktoren mit der Aufrechterhaltung von Reizen im Arbeitsgedächtnis interferieren (siehe Experimente 1a bis 2b), ist ebenso denkbar, dass Personen mit hoher Arbeitsgedächtniskapazität, die vermehrtes Rehearsal betreiben, stärker durch Distraktoren abgelenkt sind, die mit diesem Prozess interferieren (Elliott & Cowan, 2005). Die Vorhersage bezüglich der Richtung des Zusammenhangs zwischen auditiver Ablenkung und Arbeitsgedächtniskapazität hängt damit von der Definition der Arbeitsgedächtniskapazität ab, die umstritten ist (Engle, 2002; Redick, Calvo, Gay, & Engle, 2011; Unsworth & Engle, 2007; Wilhelm, Hildebrandt, & Oberauer, 2013) und im *Embedded-Processes*-Modell nicht explizit spezifiziert wird. Während es daher schwierig ist, klare Vorhersagen aus dem *Embedded-Processes*-Modell in Bezug auf die Richtung eines Zusammenhangs von auditiver Ablenkung und Arbeitsgedächtniskapazität abzuleiten, sagt das Modell eindeutig vorher, dass es keinen Unterschied im Zusammenhang zwischen Arbeitsgedächtniskapazität und dem *Changing-State*-Effekt sowie Arbeitsgedächtniskapazität und dem Devianz-Effekt geben sollte, da beide Effekte auf demselben kognitiven Mechanismus der Aufmerksamkeitsablenkung basieren. Daher sollte Arbeitsgedächtniskapazität gleichermaßen mit dem *Changing-State*-Effekt und dem Devianz-Effekt zusammenhängen oder auch nicht zusammenhängen.

Im Gegensatz dazu ist eine weitere zentrale Annahme des Duplex-Modells, dass sich die individuelle Arbeitsgedächtniskapazität unterschiedlich auf den *Changing-State*- und den

Devianz-Effekt auswirken sollte (Hughes, 2014; Hughes et al., 2013; Sörqvist, 2010). Der *Changing-State*-Effekt basiert gemäß dieses Modells auf automatischer Interferenz zwischen der Verarbeitung von Reihenfolgeinformationen der Ziel- und Distraktorreize, die unabhängig von Aufmerksamkeitsprozessen und entsprechend unabhängig von kognitiver Kontrolle der Arbeitsgedächtniskapazität ist. Das Modell sagt daher vorher, dass der *Changing-State*-Effekt nicht mit individuellen Unterschieden in der Arbeitsgedächtniskapazität zusammenhängen sollte. Der Devianz-Effekt hingegen, der auf Aufmerksamkeitsablenkung basiert, sollte stärker kognitiver Kontrolle unterliegen. Demnach wird vorhergesagt, dass sich Personen mit hoher Arbeitsgedächtniskapazität besser gegen die Aufmerksamkeitsablenkung durch deviante Distraktoren schützen können als Personen mit geringer Arbeitsgedächtniskapazität (Hughes et al., 2013; Sörqvist, 2010), eine Vorhersage die explizit auf der Definition von Arbeitsgedächtniskapazität, als Fähigkeit Ablenkung zu widerstehen (Engle, 2002), basiert. Das Modell sagt daher vorher, dass beide Effekte in unterschiedlichem Maße mit der Arbeitsgedächtniskapazität zusammenhängen sollten. Nur der Devianz- nicht aber der *Changing-State*-Effekt sollte demnach negativ mit der Arbeitsgedächtniskapazität korrelieren.

Die vorliegenden empirischen Befunde zu diesem Thema werden häufig als Beleg für einen differentiellen Zusammenhang zwischen Arbeitsgedächtniskapazität und dem *Changing-State*-Effekt auf der einen und dem Devianz-Effekt auf der anderen Seite gesehen (Hughes, 2014). Während eine Vielzahl an Untersuchungen übereinstimmend keinen Zusammenhang zwischen der Arbeitsgedächtniskapazität und dem *Changing-State*-Effekt finden konnte (Beaman, 2004; Elliott & Briganti, 2012; Hughes et al., 2013; Röer, Bell, Marsh, et al., 2015; Sörqvist, 2010; Sörqvist et al., 2013), kann die Vorhersage eines negativen Zusammenhangs zwischen der Arbeitsgedächtniskapazität und dem Devianz-Effekt jedoch aus verschiedenen Gründen angezweifelt werden. Zum einen sind die bisherigen Untersuchungsergebnisse inkonsistent. Während zwei Untersuchungen einen negativen Zusammenhang zwischen der Arbeitsgedächtniskapazität und dem Devianz-Effekt finden konnten (Hughes et al., 2013; Sörqvist, 2010), ließ sich dieser Zusammenhang in einer aktuelleren Untersuchung nicht replizieren (Röer, Bell, Marsh, et al., 2015).

Zum anderen gibt es methodische Aspekte, die weitere Untersuchungen notwenig machen. So verfügten die Studien, die einen negativen Zusammenhang zwischen der Arbeitsgedächtniskapazität und dem Devianz-Effekt finden konnten (Hughes et al., 2013; Sörqvist, 2010) über verhältnismäßig kleine Stichproben (*N* = 24 im Experiment, in dem der Devianz-Effekt untersucht wurde und *N* = 31 im Experiment, in dem der *Changing-State*-Effekt untersucht wurde in der Studie von Hughes et al., 2013; *N* = 40 in Experiment 1 und *N* = 48 in Experiment 2 von Sörqvist, 2010) im Vergleich zur Untersuchung von Röer, Bell, Marsh et al. (2015), in der sich kein solcher Zusammenhang finden ließ (*N* = 258). Dies ist ein entscheidender Aspekt, da Korrelationen innerhalb kleiner Stichproben stark variieren können, häufig ungenau sind (Schönbrodt & Perugini, 2013) und Effektstärken basierend auf kleinen Stichproben häufig überschätzt werden (Button et al., 2013). Aus diesem Grund wurden in den vorliegenden Untersuchungen vergleichsweise große Stichproben verwendet.

Zudem wurde in allen vorherigen Studien nur ein einziges Maß zur Erfassung der Arbeitsgedächtniskapazität verwendet, ein Vorgehen, welches das Risiko birgt, zu viel aufgaben- im Verhältnis zu konstruktspezifischer Varianz zu messen (Conway et al., 2005; Lewandowsky, Oberauer, Yang, & Ecker, 2010). In Experiment 3 und 4 wurden daher zwei verschiedene komplexe Arbeitsgedächtnisspannenaufgaben aus einer standardisierten und gut validierten Arbeitsgedächtnistestbatterie verwendet (Lewandowsky et al., 2010)[2].

Darüber hinaus wurde die Hypothese des Duplex-Modells, dass sich der Zusammenhang zwischen der Arbeitsgedächtniskapazität und dem *Changing-State*-Effekt von dem Zusammenhang zwischen der Arbeitsgedächtniskapazität und dem Devianz-Effekt unterscheiden sollte, nie direkt getestet. Die Schlussfolgerung eines differentiellen Zusammenhangs beider Effekte mit der Arbeitsgedächtniskapazität basierte in den vorherigen Untersuchungen (Hughes et al., 2013; Sörqvist, 2010) auf der Beobachtung, dass die Arbeitsgedächtniskapazität signifikant mit dem Devianz-Effekt, aber nicht mit dem *Changing-State*-Effekt korrelierte. Dies ist insofern problematisch, als dass eine signifikante Korrelation einerseits und eine nicht signifikan-

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[2] In Experiment 5 musste von diesem Vorgehen abgewichen werden, da es sich um eine maximal eng am Original orientierte Replikation von Experiment 1 aus der Untersuchung von Sörqvist (2010) handelt, in dem nur die Rechenspannenaufgabe verwendet wurde.

te Korrelation andererseits nicht automatisch damit gleichzusetzen ist, dass die Korrelationen sich auch signifikant voneinander unterscheiden (Gelman & Stern, 2006). Entscheidend für diese Schlussfolgerung ist es, ob die Korrelationen in einem geeigneten statistischen Test signifikant unterschiedlich voneinander sind (Diedenhofen & Musch, 2015; Nieuwenhuis, Forstmann, & Wagenmakers, 2011), was bisher nicht untersucht wurde.

Unter diesen Umständen ist es auf der Basis bisheriger Untersuchungen nicht möglich, klare Schlussfolgerungen zu ziehen. In Experiment 3, 4 und 5 der vorliegenden Arbeit wurde daher die Vorhersage des Duplex-Modells getestet, dass es (1) keine signifikante Korrelation zwischen der Arbeitsgedächtniskapazität und dem *Changing-State*-Effekt gibt, (2) eine negative Korrelation zwischen der Arbeitsgedächtniskapazität und dem Devianz-Effekt besteht und (3) sich beide Korrelationen signifikant voneinander unterscheiden.

Experiment 3

Zur Erfassung der Arbeitsgedächtniskapazität wurden in Experiment 3 zwei verschiedene komplexe Arbeitsgedächtnisspannenaufgaben, die Rechenspannenaufgabe und die Satzspannenaufgabe, verwendet, die beide einer gut validierten Arbeitsgedächtnisbatterie entnommen wurden (Lewandowsky et al., 2010). In jedem Durchgang der Rechenspannenaufgabe wurde eine mathematische Gleichung (z.B. 4+7 = 10) präsentiert, die auf ihre Richtigkeit überprüft werden sollte. Jeder Gleichung folgte ein Konsonant, der für einen späteren Abruf memoriert werden sollte. Die Anzahl an aufeinanderfolgenden Gleichungen und damit die Länge der Buchstabenlisten reichte von vier bis acht, wobei es je drei Durchgänge pro Listenlänge gab. Die Satzspannenaufgabe unterschied sich von der Rechenspannenaufgabe lediglich darin, dass statt der Gleichungen eine variierende Anzahl an Sätzen (drei bis sieben) auf ihre inhaltliche Korrektheit geprüft werden sollte (für eine detailliertere Beschreibung der Aufgaben, siehe Lewandowsky et al., 2010).

Die serielle Reproduktionsaufgabe war identisch zu der in den vorherigen vier Experimenten bis auf die Tatsache, dass die Zahlen für 300 ms mit einem 700 ms Interstimulusintervall präsentiert wurden und sie direkt (1000 ms nach ihrer Präsentation) – ohne darauf folgende

Retentionsphase – abgerufen werden sollten. Die auditiven Distraktorsequenzen bestanden wie in der Studie von Sörqvist (2010) aus einzelnen Buchstaben. Für die *Steady-State*-Sequenzen wurde ein zufällig gezogener Buchstabe aus dem Set (B, F, G, H, J, L, M, Q, R, S, T, V, Z) 18-mal hintereinander mit einer Rate von 500 ms präsentiert, wobei für jede Versuchsperson dieselbe *Steady-State*-Sequenz für alle Durchgänge verwendet wurde. Die Devianz-Bedingung war identisch zur *Steady-State*-Bedingung, abgesehen davon, dass der neunte Buchstabe durch einen zufällig gezogenen anderen Buchstaben ersetzt wurde. Für die *Changing-State*-Bedingung wurden neun Buchstaben zufällig aus dem Set gezogen und zweimal präsentiert, wobei die Präsentationsreihenfolge der Buchstaben randomisiert war. Die Präsentation der Distraktorsequenzen startete 300 ms vor der Präsentation der Zielreize, um zu garantieren, dass äquivalent zu der Untersuchung von Sörqvist (2010) der deviante Buchstabe in der Devianz-Bedingung 300 ms vor der fünften zu erinnernden Zahl präsentiert wurde. Wie in der Untersuchung von Sörqvist (2010) wurden die Experimentaldurchgänge in einen *Changing-State*- und einen Devianz-Block unterteilt. Der *Changing-State*-Block bestand aus 24 *Steady-State*- und 24 *Changing-State*-Durchgängen und der Devianz-Block aus 24 *Steady-State*- und 24 Devianz-Durchgängen. Die Reihenfolge der Durchgänge innerhalb der Blöcke war randomisiert und die Reihenfolge der Blöcke über die Teilnehmerinnen und Teilnehmer ausbalanciert. Alle Teilnehmerinnen und Teilnehmer begannen mit der Rechenspannenaufgabe, gefolgt von der Satzspannenaufgabe und der seriellen Reproduktionsaufgabe.

Zur Auswertung der Arbeitsgedächtnisaufgaben wurde für jede Listenlänge der Anteil korrekt erinnerter Buchstaben (Identität und serielle Position) berechnet und zu einem Gesamtwert aggregiert (Conway et al., 2005). Wie erwartet (Lewandowsky et al., 2010; Redick et al., 2012) korrelierte die Leistung der Teilnehmerinnen und Teilnehmer in der Rechenspannenaufgabe hoch mit der Leistung in der Satzspannenaufgabe ($r = .60$, $p < .001$), was darauf hindeutet, dass beide Aufgaben dasselbe zugrunde liegende Konstrukt messen und die Aggregation beider Werte zu einem kombinierten Wert der Arbeitsgedächtniskapazität rechtfertigt (für die deskriptiven Werte siehe Tabelle 1 in Körner, Röer, Buchner und Bell, 2017b).

Im *Changing-State*-Block war die Leistung in der seriellen Reproduktionsaufgabe stärker durch die *Changing-State*- als durch die *Steady-State*-Bedingung beeinträchtigt [$F(1,137)$ =

144.76, $p < .001$, $\eta_p^2 = .51$], während im Devianz-Block die Leistung stärker durch die Devianz- als durch die *Steady-State*-Bedingung beeinträchtigt war [$F(1,137) = 13.18$, $p < .001$, $\eta_p^2 = .09$, für die deskriptiven Werte siehe Abbildung 1 in Körner et al., 2017b]. Individuelle Unterschiede in der Ablenkbarkeit wurden wie in vorherigen Untersuchungen (Hughes et al., 2013; Röer, Bell, Marsh, et al., 2015; Sörqvist, 2010) erfasst, indem die Leistung in der *Changing-State*-Bedingung bzw. der Devianz-Bedingung von der Leistung in der korrespondierenden *Steady-State*-Bedingung subtrahiert wurde. Aufgrund der gerichteten Hypothese (negative Korrelation zwischen der Arbeitsgedächtniskapazität und auditiver Ablenkung) wurden die Korrelationen sowie der Vergleich der Korrelationen in allen Analysen einseitig getestet. Wie erwartet (Sörqvist et al., 2013) zeigte sich keine signifikante Korrelation zwischen der Arbeitsgedächtniskapazität und dem *Changing-State*-Effekt ($r = .04$, $p = .67$; siehe Abbildung 2 obere Grafik in Körner et al., 2017b), allerdings korrelierte die Arbeitsgedächtniskapazität auch nicht mit dem Devianz-Effekt ($r = -.01$, $p = .45$; siehe Abbildung 2 untere Grafik in Körner et al., 2017b). Um die zentrale Hypothese des Duplex-Modells eines unterschiedlichen Zusammenhangs zwischen der Arbeitsgedächtniskapazität und dem *Changing-State*-Effekt auf der einen und dem Devianz-Effekt auf der anderen Seite direkt zu untersuchen, wurden diese Zusammenhänge einem statistischen Test auf Unterschiede zwischen den Korrelationen (Diedenhofen & Musch, 2015; Nieuwenhuis et al., 2011; Williams, 1959) unterzogen. Die Analyse zeigte, dass sich die Korrelation zwischen der Arbeitsgedächtniskapazität und dem *Changing-State*-Effekt nicht signifikant von der Korrelation zwischen der Arbeitsgedächtniskapazität und dem Devianz-Effekt unterschied [*Williams'* $t(135) = 0.48$, $p = .32$]. Die Schlussfolgerung, dass weder der *Changing-State*-Effekt noch der Devianz-Effekt einen signifikanten Zusammenhang zur Arbeitsgedächtniskapazität aufweist, ließ sich durch Bayesianische Analysen und Regressionsanalysen bestätigen (siehe Seite 126-127 in Körner et al., 2017b).

Analog zu vorherigen Untersuchungen zeigte sich in Experiment 3 kein signifikanter Zusammenhang zwischen der Arbeitsgedächtniskapazität und dem *Changing-State*-Effekt (Hughes et al., 2013; Röer, Bell, Marsh, et al., 2015; Sörqvist, 2010; Sörqvist et al., 2013). Allerdings konnte ebenfalls kein Zusammenhang zwischen der Arbeitsgedächtniskapazität und dem Devianz-Effekt gezeigt werden und auch der Vergleich der Korrelationen widersprach den Annahmen des Duplex-Modells (Hughes, 2014), dass die Arbeitsgedächtniskapazität in unterschiedlichem Maße mit dem *Changing-State*- (keine Korrelation) und dem Devianz-Effekt (negative Korrelation) korreliert.

Aufgrund der inkonsistenten Datenlage vorheriger Untersuchungen schien es sinnvoll, die vorliegenden Befunde in einem weiteren Experiment zu replizieren. Während sich das Design von Experiment 3 weitestgehend an Experiment 1 aus der Untersuchung von Sörqvist (2010) orientierte (es wurden wie bei Sörqvist Konsonanten als Distraktoren verwendet, der auditive Deviant bestand in einer Veränderung der Stimulusidentität und die zeitliche Abfolge der Distraktoren war so gestaltet, dass die Präsentation des auditiven Deviants kurz vor der fünften zu erinnernden Ziffer erfolgte), wich das Verhältnis von *Steady-State*- zu Devianz-Durchgängen von vorherigen Untersuchungen (Hughes et al., 2013; Sörqvist, 2010) ab. Die devianten Sequenzen wurden in der Hälfte aller Durchgänge präsentiert, wohingegen in den Untersuchungen von Sörqvist (2010) und Hughes et al. (2013) nur eine geringe Anzahl an Devianz-Durchgängen (6 aus insgesamt 28 Durchgängen in der Untersuchung von Sörqvist, 2010, und 6 aus insgesamt 48 Durchgängen in der Untersuchung von Hughes et al., 2013) verwendet wurde. Da der Devianz-Effekt durch Erwartungsverletzung eines mentalen Modells erklärt wird (Nöstl et al., 2012, 2014; Röer, Bell, & Buchner, 2013; Röer et al., 2014b; Vachon, Hughes, & Jones 2012), ist es plausibel anzunehmen, dass die hohe Anzahl an Durchgängen in Experiment 3 die Vorhersagbarkeit der Devianz-Durchgänge und dadurch ihre Störwirkung beeinflusste. Daher wurde diese Hypothese in einem weiteren Experiment (Experiment 4) direkt getestet, indem das Verhältnis der Devianz-Durchgänge zu den *Steady-State*-Durchgängen manipuliert wurde. Zudem wurden im Unterschied zu Experiment 3 komplexere Distraktoren (Sätze und Wörter anstatt einzelner Buchstaben) verwendet. Diese weisen im Vergleich zu Buchstaben mehr akustische Variabilität auf, was ihre Störwirkung zusätzlich zur geringeren Anzahl an Durchgängen, verstärken (siehe Experiment 1b; Ellermeier & Zimmer, 2014; Jones & Macken, 1993; Schlittmeier et al., 2012) und damit die Wahrscheinlichkeit, eine Modulation der Störwirkung durch die Arbeitsgedächtniskapazität zu finden, erhöhen sollte.

Experiment 4

Experiment 4 war identisch zu Experiment 3 bis auf die Tatsache, dass die *Changing-State*-Sequenzen aus 24 Sätzen bestanden. Für die *Steady-State*-Sequenzen wurden 25 einsilbige Wörter aus den Sätzen verwendet, wobei jede *Steady-State*-Sequenz aus einer 18-fachen Wiederholung desselben, einsilbigen Wortes bestand. Die devianten Sequenzen waren identisch zu den *Steady-State*-Sequenzen bis auf die Tatsache, dass in jedem Durchgang das neunte Wort durch ein zufällig, ohne Zurücklegen, gezogenes anderes Wort aus den verbleibenden 24 Wörtern ersetzt wurde. Die Teilnehmerinnen und Teilnehmer absolvierten den *Changing-State*- und den Devianz-Block an zwei unterschiedlichen Tagen, wobei an beiden Tagen die Rechenspannenaufgabe und die Satzspannenaufgabe absolviert wurden. Dieses Vorgehen erlaubte es, die Retest-Reliabilität der Arbeitsgedächtnisaufgaben zu testen und die Leistung an beiden Tagen zu einem Wert zu kombinieren, was zu einer Erhöhung der psychometrischen Qualität führen sollte. Der Anteil an *Changing-State*- und Devianz-Durchgängen in jedem Block wurde als Zwischensubjektfaktor manipuliert. Die Hälfte der Teilnehmerinnen und Teilnehmer absolvierte 24 *Changing-State*- und 24 *Steady-State*-Durchgänge im *Changing-State*-Block und 24 Devianz- und 24 *Steady-State*-Durchgänge im Devianz-Block. Die andere Hälfte der Teilnehmerinnen und Teilnehmer absolvierte acht *Changing-State*- und 40 *Steady-State*-Durchgänge im *Changing-State*-Block und acht Devianz- und 40 *Steady-State*-Durchgänge im Devianz-Block. Die Zuteilung zu den Blöcken, die Reihenfolge der Blöcke und die Reihenfolge der Arbeitsgedächtnisaufgaben und der seriellen Reproduktionsaufgabe war über die Teilnehmerinnen und Teilnehmer hinweg ausbalanciert.

Die Retest-Reliabilität für die Rechenspannenaufgabe betrug r = .71 und für die Satzspannenaufgabe r = .66. Die Leistung in den beiden Aufgaben wurde über beide Tage gemittelt und aufgrund der hohen Korrelation zwischen der Leistung in beiden Aufgaben (r = .76, p < .001) zu einem Gesamtwert der Arbeitsgedächtniskapazität aggregiert (für die deskriptiven Werte siehe Tabelle 1 in Körner et al., 2017b).

Die serielle Reproduktion war stärker durch die *Changing-State*- als durch die *Steady-State*-Sequenzen im *Changing-State*-Block beeinträchtigt [F(1,61) = 99.08, p < .001, η_p^2 = .62] und stärker durch die devianten als durch die *Steady-State*-Sequenzen im Devianz-Block [F(1,61) = 22.68, p < .001, η_p^2 = .27]. Die Häufigkeit der *Changing-State*- und Devianz-Durchgänge hatte weder einen Einfluss auf die Leistung im *Changing-State*-Block [F(1,61) = 0.24, p = .63, η_p^2 < .01] noch auf die Leistung im Devianz-Block [F(1,61) = 1.50, p = .23, η_p^2 = .02] und wirkte sich nicht auf die Größe des *Changing-State*- [F(1,61) = 0.08, p = .77, η_p^2 < .01] oder des Devianz-Effektes [F(1,61) = 0.17, p = .68, η_p^2 < .01] aus (für die deskriptiven Werte siehe Abbildung 3 in Körner et al., 2017b). Da die Häufigkeit der Durchgänge in den verschiedenen Bedingungen keinen Einfluss auf die serielle Reproduktion hatte, wurde dieser Faktor in den folgenden Analysen nicht weiter berücksichtigt. Wie in Experiment 3 zeigte sich weder eine signifikante Korrelation zwischen der Arbeitsgedächtniskapazität und dem *Changing-State*-Effekt (r = -.11, p = .21; siehe Abbildung 4 obere Grafik in Körner et al., 2017b) noch zwischen der Arbeitsgedächtniskapazität und dem Devianz-Effekt (r = -.03, p = .42; siehe Abbildung 4 untere Grafik in Körner et al., 2017b). Die Korrelationen unterschieden sich auch nicht signifikant voneinander [*Williams' t*(60) = -0.46, p = .67]. Ebenfalls analog zu Experiment 3 bestätigte sich in weiteren Bayesianischen Analysen und Regressionsanalysen der Befund, dass die Arbeitsgedächtniskapazität weder mit dem *Changing-State*- noch mit dem Devianz-Effekt zusammenhing (siehe Seite 130 in Körner et al., 2017b).

Die Ergebnisse aus Experiment 4 zeigten, dass die Häufigkeit der *Changing-State*- und Devianz-Durchgänge innerhalb eines Experimentalblocks keinen Einfluss auf die Störwirkung der Distraktoren hatte. Daher kann angenommen werden, dass die Unterschiede der vorliegenden Befunde im Vergleich zu den Befunden von Sörqvist (2010) nicht auf diesen Faktor zurückzuführen sind. In bisherigen Untersuchungen blieb offen, inwiefern sich der Anteil an Devianz-Durchgängen innerhalb eines Experimentes auf die Störwirkung auswirkt. Während Experiment 2a und 2b dieser Arbeit sowie Untersuchungen von Röer et al. (2011) und Vachon et al. (2012) darauf hindeuten, dass eine Abweichung von einem regulären Muster über Experimentaldurchgänge hinweg einen Einfluss auf die Störwirkung hat, deuten andere Befunde eher daraufhin, dass es die direkt vorausgegangene auditive Stimulation (innerhalb eines Durchgangs) ist, die den größten Einfluss auf die Aufmerksamkeitsablenkung hat (Röer et al., 2014b). Die Ergebnisse aus Experiment 4 sprechen eher für letztere Annahme.

Wie in Experiment 3 war in Experiment 4 weder die Korrelation zwischen der Arbeitsgedächtniskapazität und dem *Changing-State*-Effekt noch zwischen der Arbeitsgedächtniskapazität und dem Devianz-Effekt signifikant, und unterschieden sich auch nicht voneinander. Die Ergebnisse sprechen daher genau wie die vorherigen Experimente gegen die vom Duplex-Modell postulierte Dissoziation des *Changing-State*- und des Devianz-Effektes.

Die Experimente 3 und 4 wurden als konzeptuelle Replikationen von Experiment 1 aus der Studie von Sörqvist (2010) durchgeführt. Dennoch konnte weder die Größe des Devianz-Effektes (η_p^2 = .55) noch der signifikante Zusammenhang zwischen diesem Effekt und der Arbeitsgedächtniskapazität aus der Originalstudie von Sörqvist (2010) repliziert werden. Eine mögliche Erklärung für die diskrepanten Ergebnisse könnte die verhältnismäßig kleine Stichprobe der Originaluntersuchung und das damit verbundene Risiko zur Überschätzung von Effektgrößen sein (Button et al., 2013). Eine alternative Erklärung wäre, dass die unterschiedlichen Ergebnisse in Experiment 3 und 4 im Vergleich zu Experiment 1 aus der Untersuchung von Sörqvist (2010) auf methodische Unterschiede zurückgehen. Um diese Hypothese zu überprüfen, wurde Experiment 5 als maximal eng am Original orientierte Replikation von Experiment 1 aus der Untersuchung von Sörqvist (2010) durchgeführt.

Experiment 5

Das Design von Experiment 5 glich bis auf die Anzahl der Experimentalblöcke (siehe unten) dem Design von Experiment 1 aus der Untersuchung von Sörqvist (2010). Die Arbeitsgedächtniskapazität wurde mittels einer Rechenspannenaufgabe erfasst, bei der auf die Beurteilung der mathematischen Gleichungen die Präsentation von einsilbigen Wörter zum späteren Abruf folgte. Die Länge der Wortlisten reichte von zwei bis sechs, wobei es jeweils drei Durchgänge pro Listenlänge gab. Die visuellen Zielreize bestanden aus acht Zahlen, die zufällig und ohne Zurücklegen aus den Zahlen von eins bis neun gezogen und nacheinander (750 ms Präsentationszeit, 400 ms Interstimulusintervall) in pseudorandomisierter Reihenfolge (aufeinanderfolgende Zahlen durften nicht direkt in auf- oder absteigender Reihenfolge präsentiert werden) dargeboten wurden. Die auditiven Distraktoren bestanden aus den vier Buchstaben c, k, m und j. Für die *Steady-State*-Sequenzen wurde der Buchstabe „c" 21-mal (200 ms Präsentationszeit, 100 ms Interstimulusintervall) wiederholt. Die Devianz-Bedingung entsprach der *Steady-State*-Bedingung bis auf die Tatsache, dass die 11. Wiederholung des Buchstaben „c" durch ein gesprochenes „k" ersetzt wurde. Die *Changing-State*-Bedingung unterschied sich von den anderen beiden Bedingungen lediglich dadurch, dass die vier Buchstaben (c, k, m, j) wiederholt in derselben Reihenfolge präsentiert wurden. Die Präsentation der Sequenzen erfolgte blockweise. Der *Changing-State*-Block beinhaltete 24 *Steady-State*- und sechs *Changing-State*-Durchgänge, die jeweils im 5., 9., 15., 21., 24. und 29. Durchgang des Blocks präsentiert wurden. Der Devianz-Block war identisch aufgebaut bis auf den Unterschied, dass deviante Sequenzen anstatt von *Changing-State*-Sequenzen präsentiert wurden. Die Reihenfolge der Blöcke wurde zwischen den Teilnehmerinnen und Teilnehmern ausbalanciert. Im Unterschied zum Originalexperiment von Sörqvist (2010) wurden die beiden Experimentalblöcke ein zweites Mal direkt im Anschluss an ihre erste Präsentation dargeboten mit dem Ziel, die Reliabilität der Effekte durch die verdoppelte Anzahl an Durchgängen zu erhöhen (Ellermeier & Zimmer, 1997; für eine detailliertere Diskussion zum Thema Reliabilität siehe Körner et al., 2017b). Alle Teilnehmerinnen und Teilnehmer begannen mit der Rechenspannenaufgabe und absolvierten im Anschluss die serielle Reproduktionsaufgabe.

Die Ergebnisse entsprachen den Ergebnissen aus Experiment 3 und 4. Es zeigte sich ein klassischer *Changing-State*- [$F(1,141) = 148.07$, $p < .001$, $\eta_p^2 = .51$] und ein klassischer Devianz-Effekt [$F(1,141) = 40.32$, $p < .001$, $\eta_p^2 = .22$, für die deskriptiven Ergebnisse siehe Abbildung 5 in Körner et al., 2017b]. Wie in der Originalstudie von Sörqvist (2010) gab es keinen signifikanten Zusammenhang zwischen dem *Changing-State*-Effekt und der Leistung in der Rechenspannenaufgabe ($r = .12$, $p = .93$; siehe Abbildung 6 obere Grafik in Körner et al., 2017b). Im Gegensatz zur Untersuchung von Sörqvist (2010) korrelierte die Leistung in der Rechenspannenaufgabe aber auch nicht mit dem Devianz-Effekt ($r = .09$, $p = .85$; siehe Abbildung 6 untere Grafik in Körner et al., 2017b). Ein direkter Test auf Unterschiede zwischen den Korrelationen ergab, dass sich die Korrelation zwischen der Leistung in der Rechenspannenaufgabe und dem *Changing-State*-Effekt nicht signifikant von der Korrelation zwischen der Leistung in der Rechenspannenaufgabe und dem Devianz-Effekt unterschied [*Williams' t*(139) = 0.32, $p = .37$].

Zusätzliche Bayesianische Analysen sowie Regressionsanalysen zeigten, dass die Arbeitsgedächtniskapazität weder mit der Ablenkung durch *Changing-State*- noch mit der Ablenkung durch deviante Distraktoren zusammenhing (siehe Seite 132-133 in Körner et al., 2017b). Da auch die Auswertung nur der ersten beiden Blöcke in Experiment 5 – äquivalent zur Originalstudie von Sörqvist – zu denselben Schlussfolgerungen führte (siehe Seite 133 in Körner et al., 2017b), können methodische Unterschiede zwischen Experiment 5 und Experiment 1 aus der Untersuchung von Sörqvist (2010) als Ursache für die diskrepanten Ergebnisse ausgeschlossen werden. Daher widersprechen die Ergebnisse aus Experiment 5, analog zu den Ergebnissen aus Experiment 3 und 4, den Vorhersagen des Duplex-Modells, dass die Arbeitsgedächtniskapazität in unterschiedlichem Maße mit dem *Changing-State*- und dem Devianz-Effekt zusammenhängt.

Diskussion der Experimente 3, 4 und 5

Zusammengefasst stehen die Ergebnisse der Experimente 3, 4 und 5 in klarem Widerspruch zu der Annahme des Duplex-Modells, dass die Arbeitsgedächtniskapazität in unterschiedlichem Maße mit dem *Changing-State*- und dem Devianz-Effekt zusammenhängen sollten. Ein möglicher Kritikpunkt an den vorliegenden Untersuchungen ist allerdings, dass studentische Stichproben verwendet wurden. Obwohl die Stichproben der Experimente 3, 4 und 5 über eine relativ breite Varianz in der Arbeitsgedächtniskapazität verfügten (siehe Abbildung 2, 4 und 6 in Körner et al., 2017b), ist nicht auszuschließen, dass die Varianz in nicht-studentischen Stichproben, vor allem im unteren Bereich der Arbeitsgedächtniskapazität, größer wäre. Solch eine Varianzeinschränkung kann die Wahrscheinlichkeit, eine Korrelation mit einem anderen Maß zu finden, reduzieren (Goodwin & Leech, 2006) und könnte einen Einfluss auf die Ergebnisse gehabt haben. Es ist zu beachten, dass dieser Kritikpunkt auch für die Untersuchungen von Sörqvist (2010) und Hughes et al. (2013) gilt und daher nicht für die Diskrepanzen zwischen vorherigen und den vorliegenden Ergebnissen verantwortlich sein kann. Eine Reanalyse der Daten aus Röer, Bell, Marsh et al. (2015), in der sowohl junge (zwischen 18 und 30 Jahren; N = 130) als auch ältere Erwachsene (zwischen 61 und 89 Jahren; N = 128) mit einer entsprechend großen Varianz der Arbeitsgedächtniskapazität (siehe Abbildung 7 in Körner et al., 2017b) untersucht wurden, zeigte weder einen signifikanten Zusammenhang zwischen der Arbeitsgedächtniskapazität und dem *Changing-State*-Effekt (r = .01, p = .57), noch zwischen der Arbeitsgedächtniskapazität und dem Devianz-Effekt (r = -.04, p = .25). Darüber hinaus unterschieden sich die Korrelationen nicht signifikant voneinander [*Williams' t*(255) = 0.74, p = .23]. Dies bestätigt – selbst bei großer Varianz in der Arbeitsgedächtniskapazität – und damit größerer Wahrscheinlichkeit einen Effekt im Vergleich zu vorherigen Untersuchungen (Hughes et al., 2013; Sörqvist, 2010) zu finden – das Ausbleiben eines signifikanten negativen Zusammenhangs zwischen dem Devianz-Effekt und der Arbeitsgedächtniskapazität. Das gleiche Befundmuster zeigte sich auch in einer weiteren Analyse, in der die Daten von Experiment 3, 4, 5 und der Untersuchung von Röer, Bell, Marsh et al. (2015) zu einer Gesamtstichprobengröße von N = 601 kombiniert wurden (siehe Seite 135 in Körner et al., 2017b). Die vorliegenden Daten liefern daher überzeugende Evidenz gegen eine vom Duplex-Modell postulierte Dissoziation des *Changing-State*- und des Devianz-Effektes im Hinblick auf ihren Zusammenhang zur Arbeitsgedächtniskapazität.

Allgemeine Diskussion

In der vorliegenden Arbeit wurden zwei auditive Ablenkungsphänomene, der *Changing-State*- und der Devianz-Effekt, untersucht. In der Literatur ist umstritten, ob diese durch dieselben oder unterschiedliche kognitive Mechanismen erklärt werden können. Laut dem *Embedded-Processes*-Modell (Cowan, 1995, 1999) basieren beide Effekte auf demselben kognitiven Mechanismus der Aufmerksamkeitsablenkung. Im Duplex-Modell (Hughes, 2014; Hughes et al., 2007) hingegen wird eine Dissoziation beider Effekte postuliert. Der *Changing-State*-Effekt basiert demnach auf automatischer Interferenz zwischen der Aufrechterhaltung der Zielreize und der Verarbeitung der Distraktorreize. Der Devianz-Effekt hingegen wird durch Aufmerksamkeitsablenkung erklärt, die selektiv Enkodierungsprozesse bei der seriellen Reproduktion stört. Obwohl das *Embedded-Processes*-Modell aufgrund der Sparsamkeit seiner Annahmen attraktiver erscheint (Hughes et al., 2007), wird von Vertretern des Duplex-Modells die Notwendigkeit, zwei verschiedene Prozesse zur Erklärung des *Changing-State*- und des Devianz-Effektes heranzuziehen, mit einzelnen Befunden gerechtfertigt, die auf den ersten Blick für eine funktionale Verschiedenheit beider Effekte sprechen (Hughes et al., 2005; 2007; 2013; Sörqvist, 2010; für einen Überblick siehe Hughes, 2014) und die daher essenziell für die Akzeptanz des Duplex-Modells in der wissenschaftlichen Literatur sind. Diese Befunde sind jedoch teilweise unzureichend empirisch gesichert, was eine erneute Überprüfung notwendig macht. Ziel der vorliegenden Arbeit war es daher, die Grundannahmen des Duplex-Modells und damit assoziierte Befunde exemplarisch anhand zweier prominent postulierter Dissoziationen des *Changing-State*- und des Devianz-Effektes zu testen: der Beeinträchtigung von Enkodierungs- und Gedächtnisprozessen sowie dem Zusammenhang zur Arbeitsgedächtniskapazität.

In den ersten vier Experimenten wurde untersucht, welche Zeitpunkte und damit welche kognitiven Prozesse während der seriellen Reproduktion am anfälligsten für auditive Ablenkung sind. Unabhängig von der Art der Distraktoren (*Steady-State*- und *Changing-State*-Sequenzen in Experiment 1a und 1b und deviante Sequenzen in Experiment 2a und 2b[3]) zeigte sich ein u-förmiger Verlauf der Leistung über die vier Präsentationszeitpunkte. Dieser Verlauf spiegelte sich sowohl in der Größe des *Changing-State*- als auch in der des Devianz-Effektes wider, die beide am ausgeprägtesten waren, wenn die Distraktoren in der zweiten Hälfte der Präsentation dargeboten wurden. Dies entspricht Befunden von Macken et al. (1999) und Elliot et al. (2016), die ebenfalls die größte Störwirkung von *Changing-State*-Sequenzen (im Vergleich zu Ruhe) bei der Präsentation in diesem Intervall zeigen konnten. Allerdings scheint dieser Effekt nicht, wie von Macken et al. (1999) vorgeschlagen, darauf zurückzugehen, dass die Störwirkung in Abhängigkeit der Anzahl an aufrechtzuerhaltenden Zielreizen zunimmt. In diesem Fall müsste die Störwirkung größer sein, wenn bereits alle acht Zielreize aufrechterhalten werden müssen – in Retention 1 – als wenn erst vier bis acht Zielreize zur Aufrechterhaltung dargeboten wurden – in Enkodierung 2. Die vorliegenden Befunde sprechen daher eher dafür, dass die zweite Hälfte der Präsentationsphase besonders anfällig für die Störwirkung auditiver Distraktoren ist, da die

[3] In den Experimenten 2a und 2b wurden die *Steady-State*-Sequenzen durchgehend während der Präsentation und der Retentionsphase der seriellen Reproduktion präsentiert, sodass keine zeitpunktabhängigen Effekte in dieser Bedingung zu erwarten waren.

Aufrechterhaltung einer zunehmenden Anzahl an Zielreizen mit der parallelen Enkodierung neuer Reize koordiniert werden muss. Angemessener als eine strikte Unterscheidung von Enkodierungs- und Aufrechterhaltungsprozessen in Bezug auf ihre Anfälligkeit für auditive Ablenkung scheint es daher zu sein, auditive Ablenkung als Funktion der kognitiven Belastung zu sehen, die für die Enkodierung und die Aufrechterhaltung von Informationen sowie die Koordination beider Prozesse benötigt wird, das heißt als Funktion der Gesamtbelastung des Arbeitsgedächtnisses. Darüber hinaus führte auch die Präsentation von *Changing-State*- und devianten Sequenzen in der Retentionsphase zu einer Beeinträchtigung der seriellen Reproduktion, was bedeutet, dass nicht nur *Changing-State*- sondern auch deviante Sequenzen mit der Aufrechterhaltung der Zielreize interferieren. Dies widerspricht früheren Befunden von Hughes et al. (2005), ist aber analog zu einer aktuelleren Untersuchung, in der die Präsentation eines devianten Distraktors in der Retentionsphase ebenfalls zu einer signifikanten Leistungsbeeinträchtigung führte (Röer et al., 2014b). Zusammengefasst zeigen diese Daten, dass der *Changing-State*- und der Devianz-Effekt gleichermaßen vom Präsentationszeitpunkt der Distraktoren abhängen und am stärksten in der zweiten Hälfte der Präsentation ausgeprägt sind. Dies spricht dafür, dass beide Effekte mit denselben Arbeitsgedächtnisprozessen interferieren und zur größten Störwirkung bei hoher Arbeitsgedächtnisbelastung führen.

Diese Ergebnisse lassen sich gut in die Annahmen des *Embedded-Processes*-Modells (Cowan, 1995) integrieren, laut dem *Steady-State*-, *Changing-State*- und deviante Sequenzen dieselben kognitiven Prozesse, wenn auch in unterschiedlichem Ausmaß, beeinträchtigen und ihre Störwirkung mit der Arbeitsgedächtnisbelastung durch die Aufgabe zunehmen sollte. Entsprechend der Modellvorhersagen zeigte sich ein verhältnismäßig kleiner *Changing-State*- und Devianz-Effekt, wenn die Arbeitsgedächtnisbelastung niedrig war (in Enkodierung 1) und der größte Effekt, wenn die Koordination der Aufrechterhaltung von vier bis acht Zielreizen mit der Enkodierung neuer Zielreize (in Enkodierung 2) zu einer hohen Arbeitsgedächtnisbelastung führte. Ebenfalls wie vom *Embedded-Processes*-Modell vorhergesagt, spiegelte sich dieser Verlauf in abgestuftem Maße sowohl in der *Steady-State*- und der *Changing-State*- (Experiment 1a und 1b) als auch in der Devianz-Bedingung (Experiment 2a und 2b) wider. Eine besonders wichtige Vorhersage des Modells – in Abgrenzung zum Duplex-Modell – ist es, dass auch die

Aufrechterhaltung von Informationen im Arbeitsgedächtnis Aufmerksamkeit beansprucht und daher deviante Sequenzen nicht nur mit der Enkodierung in der Präsentationsphase sondern auch mit dem Rehearsal der Zielreize in der Retentionsphase interferieren sollten, was ebenfalls durch die vorliegenden Ergebnisse bestätigt wurde.

Im Gegensatz dazu lassen sich die vorliegenden Befunde schlechter mit den Vorhersagen des Duplex-Modells (Hughes et al., 2007, 2013; Jones et al., 2010) vereinbaren. So zeigte sich in der kombinierten Analyse der Daten aus Experiment 1a und 1b ein zeitpunktabhängiger Verlauf nicht nur in der *Changing-State*- sondern auch in der *Steady-State*-Bedingung, die laut dem Duplex-Modell aufgrund fehlender Reihenfolgeinformationen nicht mit der Aufrechterhaltung von Informationen interferieren und entsprechend nicht zu zeitpunktabhängigen Effekten in der Leistung führen sollte. Die Darbietung von *Changing-State*-Sequenzen hingegen sollte am meisten stören, wenn die kognitive Belastung durch die Aufrechterhaltung der Zielreize am größten ist, also in Enkodierung 2 und Retention 1. Entsprechend dieser Vorhersage war die Leistung in der kombinierten Analyse aus Experiment 1a und 1b bei der Präsentation der Distraktoren in diesen Intervallen am schlechtesten. Allerdings spricht die größte Leistungseinbuße bei der Präsentation von Distraktoren in Enkodierung 2, bevor alle Zielreize präsentiert wurden und damit bevor das Maximum an acht Reizen aufrechterhalten werden muss, eher dafür, dass die Störwirkung mit der zunehmenden Arbeitsgedächtnisbelastung durch Enkodierungs- *und* Rehearsalprozesse ansteigt, als dafür, dass sie allein eine lineare Funktion der benötigten Aufrechterhaltungsprozesse ist. Darüber hinaus ist es eine zentrale Annahme des Duplex-Modells, dass deviante Sequenzen selektiv die Enkodierung von Informationen stören, einem Prozess, der von Aufmerksamkeitsressourcen abhängt, aber keinen Einfluss auf Aufrechterhaltungsprozesse haben soll, da diese automatisch ablaufen. Die Tatsache, dass die Darbietung von devianten Distraktoren sowohl in der Präsentationsphase (Enkodierung 1 und 2) als auch in der Retentionsphase (Retention 1 und 2) zu einem signifikanten Devianz-Effekt führte, lässt sich daher nicht mit den Modellvorhersagen in Einklang bringen.

In den Experimenten 3-5 wurde der Zusammenhang des *Changing-State*- und des Devianz-Effektes mit der Arbeitsgedächtniskapazität untersucht. Eine kleine Anzahl an Untersuchungen (Hughes et al., 2013; Sörqvist, 2010) wird häufig als Beleg dafür herangezogen, dass der *Changing-State*-Effekt nicht mit der Arbeitsgedächtniskapazität assoziiert ist, während der Devianz-Effekt bei Personen mit hoher Arbeitsgedächtniskapazität reduziert ist. Im Vergleich zu diesen Untersuchungen enthielten die Experimente 3 und 4 methodische Verbesserungen (große Stichproben, einseitige Tests zur Überprüfung der Zusammenhänge, einen direkten Test zum Vergleich der Korrelationen sowie verschiedene Arbeitsgedächtnisaufgaben zur Messung der Arbeitsgedächtniskapazität), die die Wahrscheinlichkeit einen differentiellen Zusammenhang zwischen auditiver Ablenkung durch *Changing-State*- und deviante Distraktoren und der Arbeitsgedächtniskapazität zu finden, erhöhen sollten. Im Einklang mit vorherigen Untersuchungen (Hughes et al., 2013; Röer et al., 2015; Sörqvist, 2010; Sörqvist et al., 2013) konnte kein Zusammenhang zwischen der Arbeitsgedächtniskapazität und dem *Changing-State*-Effekt gefunden werden. Allerdings zeigte sich ebenfalls kein Zusammenhang zwischen der Arbeitsgedächtniskapazität und dem Devianz-Effekt. Dies widerspricht bisherigen Untersuchungen mit kleinen Stichproben (Hughes et al., 2013, Sörqvist, 2010), ist aber analog zu den Befunden von Röer, Bell, Marsh, et al. (2015) unter der Verwendung einer erheblich größeren Stichprobe. Entscheidend ist darüber hinaus, dass sich die Korrelationen zwischen der Arbeitsgedächtniskapazität und dem *Changing-State*-Effekt sowie der Arbeitsgedächtniskapazität und dem Devianz-Effekt nicht signifikant unterschieden, was klar gegen eine Dissoziation beider Effekte spricht. Diese Befunde konnten in Experiment 5, einer maximal eng am Original orientierten Replikation von Experiment 1 aus der Untersuchung von Sörqvist (2010), sowie einer Reanalyse der Daten aus Röer, Bell und Marsh et al. (2015), in die Daten von jungen und älteren Erwachsenen mit entsprechend breiter Varianz der Arbeitsgedächtniskapazität eingingen, bestätigt werden. Methodische Unterschiede als Ursache für diskrepante Ergebnisse zwischen den vorliegenden Experimenten und der Untersuchung von Sörqvist (2010) sowie eine Varianzeinschränkung der Arbeitsgedächtniskapazität als Ursache für ausbleibende Zusammenhänge der auditiven Ablenkung mit der Arbeitsgedächtniskapazität können daher ausgeschlossen werden.

Wieder lassen sich die Befunde gut mit den Annahmen des *Embedded-Processes*-Modells (Cowan, 1995, 1999) erklären, welches die klare Vorhersage macht, dass der *Changing-State*- und der Devianz-Effekt, die auf demselben Mechanismus der Aufmerksamkeitsablenkung beruhen, gleichermaßen mit der Arbeitsgedächtniskapazität zusammenhängen sollten.

Wie eingangs beschrieben, hängen die Vorhersagen bezüglich der Richtung, in der die Arbeitsgedächtniskapazität mit auditiver Ablenkung zusammenhängen sollte, von der Definition der Arbeitsgedächtniskapazität ab, die umstritten ist (Engle, 2002; Redick et al., 2011; Unsworth & Engle, 2007; Wilhelm et al., 2013) und zu der im *Embedded-Processes*-Modell keine spezifischen Aussagen getroffen werden. Gemäß der Definition von Arbeitsgedächtniskapazität des Ansatzes exekutiver Aufmerksamkeit (Engle, 2002) wird häufig aus dem *Embedded-Processes*-Modell abgeleitet, dass Personen mit hoher Arbeitsgedächtniskapazität weniger durch auditive Distraktoren abgelenkt sein sollten als Personen mit geringer Arbeitsgedächtniskapazität (Elliott, 2002; Elliott & Cowan, 2005; Hughes et al., 2013; Sörqvist, 2010; Sörqvist, Marsh, & Nöstl, 2013). Ausgehend von der Annahme, dass Arbeitsgedächtniskapazität die Fähigkeit abbildet, Informationen durch Rehearsal aufrechtzuerhalten (Unsworth & Engle, 2007), ist es allerdings genauso denkbar, dass Personen mir hoher Arbeitsgedächtniskapazität stärker durch auditive Distraktoren abgelenkt sind, die genau diesen Rehearsalprozess stören (Elliott & Cowan, 2005). Da im Modell keine konkreten Vorhersagen in Bezug auf die Richtung dieses Zusammenhangs gemacht werden, eignet sich die Richtung des Effektes nicht, um das Modell zu testen. Entsprechend unerheblich für die Gültigkeit des Modells ist daher die spezifische Richtung des Zusammenhangs zwischen der Arbeitsgedächtniskapazität und auditiver Ablenkung, solange sich keine Unterschiede in diesem Zusammenhang in Abhängigkeit der Art der Distraktoren – *Changing-State* oder deviante Distraktoren – zeigen.

Die Befunde stehen jedoch im deutlichen Widerspruch zu den Annahmen des Duplex-Modells (Hughes, 2014; Hughes et al., 2013), das die klaren Vorhersagen macht, dass der Devianz-Effekt negativ mit der Arbeitsgedächtniskapazität korrelieren sollte, während ein Zusammenhang zwischen der Arbeitsgedächtniskapazität und dem *Changing-State*-Effekt ausbleiben sollte, und dass sich diese Korrelationen signifikant voneinander unterscheiden. Die Tatsache, dass auditive Ablenkung unabhängig von der Art der Distraktoren nicht mit der Arbeitsgedächtniskapazität korrelierte und sich auch kein Unterschied zwischen den Korrelationen zeigte, widerspricht diesen Hypothesen und bietet daher direkte Evidenz gegen eine weitere der postulierten Dissoziation des *Changing-State*- und des Devianz-Effektes, die die empirische Basis des Duplex-Modells bilden.

Die Ergebnisse der vorliegenden sieben Experimente sprechen damit eindeutig gegen die vom Duplex-Modell postulierte Dissoziation des *Changing-State*- und des Devianz-Effektes, die sich unter anderem in ihrer unterschiedlichen Beeinträchtigung von Enkodierungs- und Gedächtnisprozessen oder ihres unterschiedlichen Zusammenhangs zur Arbeitsgedächtniskapazität zeigen sollte. Beide Effekte basieren auf der Störung von Gedächtnisprozessen durch abrupte Veränderungen akustischer Reizeigenschaften. Eine Erklärung durch einen einzigen kognitiven Mechanismus der Aufmerksamkeitsablenkung, wie vom *Embedded-Processes*-Modell vorgeschlagen, ist daher allein aufgrund der Sparsamkeit seiner Annahmen einer Erklärung vorzuziehen, die zwei verschiedene zugrunde liegende kognitive Prozesse der oberflächlich so ähnlichen Effekte vorsieht. Aus diesem Grund hängt das Duplex-Modell stark von der Überzeugungskraft empirischer Befunde ab, die eine Dissoziation der vermeintlich so ähnlichen Effekte belegen. Die Ergebnisse der vorliegenden sieben Experimente entziehen dem Modell einen Teil dieser empirischen Basis, die im Vergleich zu den vorliegenden Daten auf einer kleinen Anzahl an Experimenten mit sehr kleinen Stichproben und methodischen Schwächen basiert. Die vorliegenden Ergebnisse liefern damit eine tragfähige Argumentationsgrundlage gegen eine Dissoziation der Effekte, welche in Einklang mit weiteren aktuellen Befunden zu sehen ist, die beispielsweise keine Evidenz für eine unterschiedliche Abnahme des *Changing-State*- und des Devianz-Effektes über Experimentaldurchgänge hinweg (Röer, Bell, Marsh, et al., 2015) oder die unterschiedliche Modulation der Effekte durch Vorabinformation finden konnten (Röer, Bell, & Buchner, 2015). Zusammen betrachtet, stellt diese breite Befundlage den Gültigkeitsanspruch des Duplex-Modells zur Erklärung auditiver Ablenkung ernsthaft in Frage. Weitere postulierte, aber bisher noch nicht systematisch überprüfte Dissoziationen der Effekte, wie beispielsweise die Beeinflussung des Devianz- nicht aber des *Changing-State*-Effektes durch perzeptuelle Maskierung der Zielreize (Hughes et al., 2013) oder die Annahmen, dass sich der *Changing-State*-Effekt nur bei Aufgaben, die serielles Rehearsal erfordern, zeigen sollte (Hughes et al., 2007), sollten daher in Zukunft systematisch überprüft, bevor sie unkritisch akzeptiert werden. Die vorliegenden Befunde sprechen damit für einen einheitlichen kognitiven Mechanismus der Aufmerksamkeitsablenkung als Erklärung beider Ablenkungsphänomene, wie sie das *Embedded-Processes*-Modell (Cowan, 1995, 1999) vorsieht.

Zusammengefasst liefern die vorliegenden Befunden überzeugende Evidenz dafür, dass die vom Duplex-Modell zentral postulierte Dissoziation des *Changing-State*- und des Devianz-Effektes eher auf methodischen Artefakten als auf verschiedenen zugrunde liegenden kognitiven Mechanismen beruht. Die Befundlage spricht damit dafür, dass der *Changing-State*- und der Devianz-Effektes auf ähnlichen Arbeitsgedächtnisprozessen beruhen, und stellt die Legitimation des Duplex-Modells als Erklärungsmodell auditiver Ablenkung in Frage.

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Experimente 1b - 2b

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Experimente 3 - 5

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Time of presentation affects auditory distraction: Changing-state and deviant sounds disrupt similar working memory processes

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Abstract

Four experiments tested conflicting predictions about which components of the serial-recall task are most sensitive to auditory distraction. Changing-state (Experiments 1a and 1b) and deviant distractor sounds (Experiments 2a and 2b) were presented in one of four different time intervals of the serial recall task: (1) during the first half of encoding, (2) during the second half of encoding, (3) during the first half of retention, or (4) during the second half of retention. According to the embedded-processes model, both types of distractors should interfere with the encoding and rehearsal of target items in the focus of attention. According to the duplex account, changing-state distractors should interfere only with rehearsal while deviant distractors should interfere only with encoding. Inconsistent with the latter view, changing-state and deviant distractor sounds interfered with both the encoding and the retention of the target items. Both types of auditory distraction were most pronounced during the second half of encoding when the increasing rehearsal demands had to be coordinated with the continuous updating of the rehearsal set. These findings suggest that the two types of distraction disrupt similar working memory mechanisms.

Time of presentation affects auditory distraction: Changing-state and deviant sounds disrupt similar working memory processes

There is ample evidence that background sound adversely affects cognitive performance (Bell, Dentale, Buchner, & Mayr, 2010; Campbell, Beaman, & Berry, 2002; Colle & Welsh, 1976; Elliott & Briganti, 2012; Jones, Madden, & Miles, 1992; Parmentier, 2014; Röer, Bell, Dentale, & Buchner, 2011; Vachon, Hughes, & Jones, 2012). While there is a general consensus that distraction is primarily determined by the occurrence of abrupt changes in the to-be-ignored auditory stream (Ellermeier & Zimmer, 2014; Schlittmeier, Weißgerber, Kerber, Fastl, & Hellbrück, 2012; Tremblay & Jones, 1999), there is less consensus about the types of processes that are disrupted by task-irrelevant background sound. Different explanations of auditory distraction (Cowan, 1995; Hughes, Vachon, & Jones, 2005, 2007) yield conflicting predictions about the mechanisms that are responsible for the performance decrements, and, in consequence, about the types of processes that are susceptible to different types of auditory distraction. We tested these predictions by examining at which time intervals serial recall is most vulnerable to the disruption by changing-state and deviant distractor sounds.

The serial-recall task is one of the standard paradigms to examine the detrimental effects of background sound on cognitive performance. Participants typically memorize a sequence of visually presented target items while ignoring auditory distractors. Immediately after the presentation of the target items or after a short retention interval, the target items have to be recalled in the order of their presentation. Depending on the time interval, different information-processing mechanisms are recruited by the serial-recall task (Hughes et al., 2005; Macken, Mosdell, & Jones, 1999). During target-item presentation, new target items have to be encoded while an increasing number of already-presented items have to be rehearsed in working memory. During the presentation of the first half of the list, the burden on encoding is high while the burden on rehearsal is comparatively low because the memory set is below the span of items that can be held simultaneously in the focus of attention (Cowan, 2001). During the presentation of the second half of the list, the burden on encoding remains high and coincides with a high burden on rehearsal because the number of target items is above span, which means that the target items have to be continuously refreshed to be retained in working memory. During the retention interval, encoding is completed, but it is still necessary to rehearse the target items to maintain them in an accessible state. Therefore, the task gets somewhat easier because it is no longer necessary to coordinate the encoding of new items with the parallel rehearsal of old items, but the task still relies heavily on rehearsal processes until the memory representation may eventually become more stable over time (Macken et al., 1999).

Serial recall is markedly disrupted by different types of auditory distractors. Three types of auditory distractors are usually distinguished. Steady-state sequences consisting of regular repetitions of a single distractor word (e.g., “test, test, test, test, test, test, test, test”) disrupt serial recall in comparison to a quiet control condition (LeCompte, 1995), but cause less distraction than more variable distractor sequences. Changing-state sequences consisting of different distractor words (e.g., “song, end, friend, thing, hand, folk, child, time”) cause more distraction than steady-state sequences (Bell et al., 2010; Campbell et al., 2002; Jones & Macken, 1993; Parmentier & Beaman, 2014; Schlittmeier, Hellbrück, & Klatte, 2008). The difference between the steady-state condition and the changing-state condition is referred to as the changing-state effect (see, e.g., Hughes et al., 2005, 2007). The changing-state effect is often contrasted with the deviation effect, which refers to the disruption of serial recall caused by singular violations of regular patterns in the unfolding auditory stimulation (Hughes et al., 2005, 2007; Lange, 2005; Sörqvist, 2010). Usually, the deviation effect is measured by comparing the disruptive effect of deviation sequences—steady-state sequences with a single deviant distractor item (e.g., “test, test, test, test, test, song, test, test”)—with that of regular steady-state sequences (Röer, Bell, Marsh, & Buchner, 2015; Röer, Körner, Buchner, & Bell, in press; Sörqvist, 2010).

Unitary theories take into account that the changing-state effect and the deviation effect appear to be very similar at first glance: changes in the auditory modality cause a disruption of serial recall. The embedded-processes model (Cowan, 1995, 1999) postulates that both types of auditory distraction are caused by the same attentional orienting mechanism. The to-be-remembered target items have to be successively brought into the focus of attention to encode them and to maintain them in working memory. When focal attention is drawn away from the target items, they lose activation and are thus less likely to be successfully recalled. Compared to a quiet control condition, steady-state sequences may capture a small amount of attention (because the system should never fully habituate to the abrupt onsets of the distractors or else the organism would risk missing potentially relevant changes in the environment), but they should capture less attention than changing-state and deviation sequences because the neural system adapts to distractor repetitions, which decreases the likelihood that repeated distractors capture attention. When changing-state sequences are played, the continuous changes from one distractor item to another cause recurring shifts of attention towards the auditory modality. Likewise, a single deviation from a regular steady-state sequence causes dishabituation, and is therefore a potent source of attentional capture. If the focus of attention is not fully available for the encoding and rehearsal of the target items, a performance decrement results. In essence, then, both changing-state and deviant distractors are assumed to interfere with the active, intentional process of bringing target items into the focus of attention during encoding and rehearsal. This model leads to the prediction that changing-state and deviant distractors should disrupt encoding and retention in working memory. The degree of this disruption should increase as a function of the degree to which encoding and rehearsal of the target items place a burden on working memory.

The duplex-mechanism account (Hughes, Hurlstone, Marsh, Vachon, & Jones, 2013; Hughes et al., 2007; Jones, Hughes, & Macken, 2010) postulates that the changing-state effect and the deviation effect are caused by two separate mechanisms. The changing-state effect is attributed to the interference between two seriation processes. Rehearsal serves to voluntarily maintain the order of the target sequences via seriation, “the process of placing events in serial order” (Tremblay, Nicholls, Alford, & Jones, 2000, p. 558). The order of to-be-ignored changing-state distractors is automatically registered by an obligatory order-processing mechanism. This preattentive, automatic seriation of the auditory background sound relies on the same processes as the seriation of the target items. These seriation processes are occupied with the processing of the distractor information, and are therefore not fully available for the voluntary maintenance of the order of the target items (Jones et al., 2010). Steady-state distractors, in contrast, do not contain any order cues that can interfere with the seriation of the target items. Therefore, the changing-state effect should increase with the demands the task imposes on seriation, which in turn increases with the number of items that have to be maintained in the correct order. An involvement of attentional mechanisms in the changing-state effect is explicitly excluded.

The deviation effect, in contrast, is attributed to attentional capture by auditory deviations that draw the focus of attention away from the primary task. However, if seriation does not involve attention, the withdrawal of attention should have no effect on the seriation of the target items. This is exactly what the authors of the duplex account propose when they suggest that "some types of cognitive activity—arguably ones that represent postencoding processes—seem immune to a deviation effect" (Hughes et al., 2005, p. 746). Instead, attentional capture is assumed to disrupt the encoding of the to-be-remembered stimuli while it does not interfere with seriation (Hughes et al., 2007; 2013; Jones et al., 2010). In other words, only the encoding of the target items, but not their retention in working memory, depends on attentional resources, and is therefore impaired by attentional capture. To sum up, the model predicts that the changing-state effect interferes with serial rehearsal while the deviation effect is restricted to encoding.

Some earlier studies have provided preliminary support of such a dissociation by demonstrating that the amount of distraction by changing-state sequences is independent of whether the distractors are presented during encoding or retention (Buchner, Rothermund, Wentura, & Mehl, 2004; Elliott et al., 2016; Miles, Jones, & Madden, 1991), which suggests that changing-state distractors interfere with the maintenance of the items in working memory, but not with encoding. Macken and colleagues (1999) provided a more fine-grained analysis of how time of presentation determines distraction by changing-state sequences. Presenting changing-state distractors in an interval prior to encoding had no effect on serial recall at all. Playing the same distractors in the first half of the encoding interval produced a small and nonsignificant distraction effect. The largest performance decrement relative to the quiet control condition was found when the changing-state distractors were presented in the second half of the encoding interval. Presenting the distractors in the first half of the retention interval also caused a considerable performance decrement. Presenting the items in the second half of the retention interval caused a somewhat smaller, but still significant, disruption of serial recall. Macken et al. (1999) concluded that the changing-state effect is caused by a disruption of serial rehearsal, and increases with the burden the task places on this process. There is no burden on rehearsal before target presentation, a low burden in the first half of the encoding interval when the memory set is below span, and a high burden in the second half of the encoding interval when the number of items that have to be retained in memory are above span. To explain the reduction of distraction in the second half of the retention interval, Macken et al. proposed that the continued rehearsal of the target items may eventually result in a stable memory representation that is relatively insensitive to distraction.

According to the duplex account (Hughes et al., 2007; 2013; Jones et al., 2010), time of presentation should have a different effect on the disruption by deviant stimuli because deviants are assumed to disrupt encoding and not retention. This prediction was seemingly supported by Hughes et al.'s (2005) findings that the deviation effect was obtained in their Experiment 1 in which the deviant was presented during the encoding of the target items, but not in their Experiment 2, in which the deviant was presented in a retention interval. The authors concluded that the attentional capture by the auditory deviant disrupted the intake of information, but had no effect on the serial rehearsal of the target material, which was postulated to be independent of focal attention.

Although this result has been characterized as "one of the most notable" dissociations between the changing-state effect and the deviation effect (Jones et al., 2010, p. 205), a closer examination of Hughes et al.'s (2005) findings suggests that the dissociation is not clearly substantiated. In fact, the results by Hughes et al. can even be considered consistent with the pattern identified by Macken et al. (1999) because Hughes et al. found a deviation effect when the deviant was presented in the second half of the encoding interval, which, according to Macken et al. (1999), is particularly susceptible to distraction; no deviation effect was found when the deviant occurred in the second half of the retention interval (more than 4 s after the presentation of the last target item), which was identified by Macken et al. (1999) as being relatively insensitive to distraction. Furthermore, the critical comparison was between experiments, one of which employed different (immediate vs. delayed) serial-recall tasks. Consistent with other studies (Elliott & Cowan, 2005), delaying recall generally decreased auditory distraction. In Experiment 1—in which the distractor sequences were played during the encoding interval—participants were required to recall the items immediately (50 ms) after the offset of the last visual target item. In this experiment, the changing-state effect ($\eta_p^2 = .68$) was much larger than the deviation effect ($\eta_p^2 = .23$), but both effects were significantly different from zero. In Experiment 2—in which the distractor sequences were played during retention—recall was delayed by seven seconds. In consequence, both the changing-state effect ($\eta_p^2 = .37$) and the deviation effect ($\eta_p^2 = .05$) were smaller than in Experiment 1. Although the deviation effect failed to reach statistical significance with a total sample size of only $N = 29$, the reduction in effect size from Experiment 1 to Experiment 2 was even more pronounced for the changing-state effect. Therefore, these findings do not provide definitive evidence in favor of the hypothesized dissociation.

Is the changing-state effect influenced by time of distraction?

The aim of the present study was to gain insight into the types of mechanisms that are disrupted by changing-state and deviant distractors. Experiments 1a and 1b served to identify the time intervals that are most susceptible to the changing-state effect, using both steady-state and changing-state distractors. The pioneering study of Macken et al. (1999), included only changing-state distractors (presented at different time intervals) and a quiet control condition, but no steady-state control condition. A recent study employing the same paradigm (Elliott et al., 2016) also lacks a steady-state control condition. In consequence, it is as yet unclear whether the effect of time of distraction on serial recall is due to auditory distraction in general or to the changing-state effect in particular. This is an important distinction because the duplex account specifically predicts that the changing-state effect (defined as the difference between the changing-state condition and the steady-state condition, see Hughes et al., 2005, 2007) should vary as a function of rehearsal load. Performance in the steady-state condition, in contrast, should not vary as a function of rehearsal load because steady-state distractors should not interfere with seriation. To test this theoretical prediction, it is necessary to examine the changing-state effect, and to compare the changing-state condition with a steady-state control condition.

The steady-state condition is the standard control condition in almost all experiments testing the predictions of the duplex account (Hughes et al., 2005; 2007, 2013), but to our knowledge there are no published findings on how the difference between the changing-state and the steady-state condition varies as a function of time of presentation. Therefore, we used the same procedure as Macken et al. (1999), but we presented both changing-state and steady-state sequences at those four time intervals that are theoretically most important: (1) the first half of the encoding interval (Encoding 1), (2) the second half of the encoding interval (Encoding 2), (3) the first half of the retention interval (Retention 1), and (4) the second half of the retention interval (Retention 2).[1] This allowed us to test how the changing-state effect is affected by time of presentation. The duplex account (Hughes et al., 2007, 2013; Jones et al., 2010) predicts that the changing-state effect should be small when the distractors are presented at Encoding 1 because there is only a small burden on seriation. The effect should be large when the distractors are presented at Encoding 2 and at Retention 1 because the burden on seriation is high. Possibly, the changing-state effect may decrease at Retention 2 because the continuous seriation of the target items may result in a stable target-sequence representation (Macken et al., 1999). Steady-state distractors, in contrast, are assumed to lack irrelevant order cues and to be impotent in their capacity to interfere with seriation. Therefore, the duplex account predicts that the effects of time of presentation should be specific to the changing-state condition, and should be absent in the steady-state condition, resulting in a significant interaction between distractor type and time of presentation.

According to the embedded-processes model (Cowan, 1995), attention is required to encode and rehearse the target items. The withdrawal of attention away from the primary task

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[1] Macken et al. (1999) included a condition in which the auditory distractors were presented prior to the presentation of the target items. Presenting distractors before target presentation did not affect serial recall at all. Given that this finding is to be expected based on all current theoretical accounts, we decided against including this time interval in the present experiments.

should disrupt performance when these processes place a high burden on attentional resources. The serial-recall task should be relatively easy as long as the number of to-be-remembered items is below four (Cowan, 2001), but the attentional demands should drastically increase when a larger number of items has to be refreshed by being brought back into the focus of attention, and when the continuous presentation of target items requires the updating of the rehearsal set. Changing-state sequences should capture more attention than steady-state sequences, but the onset of each steady-state distractor may also capture some amount of attention before the system can match the representation of the current distractor with its representation in memory. Therefore, the model predicts that performance should be worse when distractors are played at Encoding 2 relative to Encoding 1, should remain poor when distractors are played at Retention 1, and may possibly recover when a stable representation of the target sequence has been established via continuous rehearsal at Retention 2. This pattern should occur regardless of distractor type, but should be more pronounced for changing-state distractors than for steady-state distractors because changing-state distractors are assumed to capture more attention than steady-state distractors (Cowan, 1995).

Experiment 1a

Method

Participants. Ninety students (63 women) at Heinrich Heine University Düsseldorf aged 19 to 40 years (M = 26) participated in exchange for course credit or a small honorarium. All reported normal hearing and normal or corrected-to-normal vision and were fluent German speakers.

Materials. The visually presented target sequences consisted of eight digits sampled randomly without replacement from the set {1,2,…, 9}. The digits were presented in 72-point equidistant black Monaco font on a white background in the center of a 21.5-inch computer screen. Participants were seated about 45 cm from the screen, hence the visual angle of the digits subtended 1.49° vertical and 0.92° horizontal.

Auditory distractors consisted of 32 steady-state and 32 changing-state sequences composed of eight one-syllable German nouns (translation in parentheses): Alm (alp), Elch (moose), Gel (gel), Jod (iodine), Milz (spleen), Schopf (tuft), Streu (mulch), Tau (dew), which were used as distractors in previous studies (Röer, Bell, & Buchner, 2015a; Röer et al., 2011). All words were spoken by the same male voice, digitally recorded at 44.1 kHz using 16-bit encoding, edited to last 500 milliseconds and normalized to minimize amplitude differences among the stimuli.

Each of the 32 steady-state sequences consisted of eight repetitions of a single distractor word; thus each word of the distractor set was used four times as a steady-state sequence during the course of the experiment. For the changing-state sequences, 32 random orders of the eight one-syllable nouns were created and used for all participants to be played as auditory distractors in the changing-state condition. All sequences were four seconds long and were played over headphones at an average sound level of about 55 dB(A).

Procedure. Participants were informed that they should ignore any sound presented through the headphones and that they should not vocalize any to-be-remembered digits. To signal the start of each trial, a red traffic light was presented, which turned yellow and then green. After that the trial started with the consecutive presentation of the eight digits (800 ms on, 200 ms off). The eight-second encoding interval was followed by an eight-second retention interval, after which the digits had to be recalled in the order of their presentation. Eight question marks were shown, and participants were required to replace the question marks by pressing the keys on the number keypad. Participants could not correct their answers, but they could indicate that they did not remember a certain digit by pressing a “don’t know” button. When all question marks were replaced with digits, the participants could start the next trial by pressing the space bar. Participants started with two quiet training trials before completing 64 experimental trials. As illustrated in Figure 1, the changing-state distractor sequences and the steady-state distractor sequences were played during one of four different time intervals in the experimental trials (Encoding 1, Encoding 2, Retention 1, Retention 2). Eight sequences of each type were presented in each of the four conditions. Each participant saw the trials in a different, randomized order[2].

Design. The experiment had a 2 × 4 repeated-measures design with distractor type (steady-state, changing-state) and time of distraction (Encoding 1, Encoding 2, Retention 1, Retention 2) as independent variables and serial recall as the dependent variable. The answers were only scored as correct when the digits were recalled in the exact serial position in which they had been presented. Of primary interest was the possible interaction between distractor type and time of distraction. Given a total sample size of $N = 90$, $\alpha = .05$, and $\rho = .30$, an interaction of $f = .19$ could be detected with a probability of $1 - \beta = .95$. All power calculations reported in this article were conducted with G*Power (Faul, Erdfelder, Lang, & Buchner, 2007).

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[2] For the procedure of all experiments described in this manuscript a positive ethical approval of the Ethic-Committee of the Faculty of Mathematics and Natural Sciences of the Heinrich-Heine-University Düsseldorf was obtained.

A multivariate approach was used for all within-subjects comparisons. In the present application, all multivariate test criteria correspond to the same (exact) F statistic, which is reported. The level of alpha was set to .05 for all analyses.

Results

Table 1 shows the mean serial recall performance in the changing-state and in the steady-state condition, as well as the differences between these two conditions, as a function of time of distraction. A 2 × 4 repeated-measures MANOVA confirmed that participants performed better in the steady-state condition compared to the changing-state condition $F(1,89) = 35.23$, $p < .001$, $\eta_p^2 = .28$, which confirms the typical changing-state effect for the present experiment. Performance was significantly affected by time of distraction, $F(3,87) = 22.16$, $p < .001$, $\eta_p^2 = .43$. The results show a U-shaped association between time of distraction and serial recall in both distractor conditions, consistent with the findings of Macken et al. (1999). Most importantly, the interaction between distractor type and time of distraction just missed the conventional level of statistical significance, $F(3,87) = 2.52$, $p = .06$, $\eta_p^2 = .08$. There was a changing-state effect at all four time intervals: at Encoding 1, $F(1,89) = 8.66$, $p < .01$, $\eta_p^2 = .09$, at Encoding 2, $F(1,89) = 24.90$, $p < .001$, $\eta_p^2 = .22$, at Retention 1, $F(1,89) = 4.21$, $p = .04$, $\eta_p^2 = .05$, and at Retention 2, $F(1,89) = 4.26$, $p = .04$, $\eta_p^2 = .05$, but the effect was descriptively most pronounced when the distractors were played at Encoding 2.

Discussion

When only the changing-state condition is considered, the present study replicates the findings of Macken et al. (1999) perfectly. Performance was best when the distractors were presented when the burden on rehearsal was low (at Encoding 1), and worst when the distractors were presented when the burden on rehearsal was high (at Encoding 2 and at Retention 1). According to the duplex account (Hughes et al., 2007, 2013; Jones et al., 2010), this pattern is caused by a differential sensitivity of different stages of serial recall to the changing-state effect. According to this explanation, performance in the steady-state condition should not be affected by time of presentation while the changing-state effect (the difference between the changing-state condition and the steady-state condition) should be least pronounced when rehearsal load is low (at Encoding 1) and most pronounced when rehearsal load is high (at Encoding 2 and Retention 1). Given that the interaction between distractor type and time of distraction failed to reach significance in Experiment 1 (although sample size and, therefore, statistical power was much larger than in previous experiments), it is possible to conclude that this interpretation is not supported by the present results. Given that there was a main effect of time of distraction on serial recall, the results are more in line with a generally enhanced sensitivity to distraction at the time intervals with increased rehearsal load, as indicated by the fact that performance in both distractor conditions was decreased when the distractors were played at Encoding 2 and Retention 1. Thus, our data suggest that the changing-state effect does not vary as a function of time of distraction and that the observed pattern might not be specific to changing-state distractors, but may be typical for auditory distraction per se. This is inconsistent with the duplex account, which assumes that only changing-state stimuli interfere with serial rehearsal while steady-state stimuli do not contain irrelevant order cues that may interfere with the rehearsal process.

However, one might argue that the foregoing discussion represents a too strict interpretation of significance because the critical interaction between distractor type and time of distraction only just failed to reach the conventional level of statistical significance. Numerically, the changing-state effect was more pronounced when the distractors were played at Encoding 2, which is consistent with the predictions of Macken et al. (1999) at a descriptive level. Therefore, it may be premature to reject the idea that the changing-state effect varies as a function of time of distraction. To get a clearer picture, we decided to collect more data to disambiguate the results.

Experiment 1b

Experiment 1b was parallel to Experiment 1a, except that we used sentential speech as distractor material, as in the pioneering study of Macken et al. (1999). Compared to sequences of monosyllabic words, sentences contain more changes in rhythm and frequency—which are assumed to be primarily responsible for distraction (Tremblay et al., 2000)—and, therefore, do often cause more disruption of serial recall than word lists (e.g., Röer, Bell, & Buchner, 2015b), which may facilitate observing a modulation of this effect by time of distraction.

Method

Participants. Seventy-nine students (47 women) at Heinrich Heine University Düsseldorf aged 18 to 45 years (M = 26) participated in exchange for course credit or a small honorarium. All reported normal hearing and normal or corrected-to-normal vision and were fluent German speakers.

Materials, Procedure, and Design. Materials, procedure, and design were identical to those of Experiment 1a except that more complex distractor material (similar to that used by Bell, Röer, Dentale, & Buchner, 2012) was used. The changing-state sequences consisted of 32 German spoken texts, taken from different categories (weather forecast, prose text, cooking recipe, scientific textbook, poem, operating manual, road message, aphorism). One monosyllabic word from every sentence was selected for the 32 steady-state control sequences. The sentences were, on average, 8.34 words long. The number of single word repetitions in the steady-state sequences was matched to the number of words in the changing-state sequences. Each distractor sequence was four seconds long (as in Experiment 1a).

Given a total sample size of $N = 79$, $\alpha = .05$, and $\rho = .30$, an interaction between distractor type and time of distraction of size $f = .20$ could be detected with a probability of $1 - \beta = .95$.

Results

Table 1 shows the mean serial recall performance in the changing-state and in the steady-state condition, as well as the differences between the two conditions, as a function of time of distraction. A typical changing-state effect was found, $F(1,78) = 51.09$, $p < .001$, $\eta_p^2 = .40$. There was also a significant main effect of time of distraction, $F(3,76) = 31.96$, $p < .001$, $\eta_p^2 = .56$. Importantly, the interaction between distractor type and time of distraction was also significant, $F(3,76) = 5.05$, $p < .01$, $\eta_p^2 = .17$. The changing-state effect was not significant when the distractors were played at Encoding 1, $F(1,78) = 1.44$, $p = .23$, $\eta_p^2 = .02$, but it was significant when the distractors were played at Encoding 2, $F(1,78) = 20.35$, $p < .001$, $\eta_p^2 = .21$, at Retention 1, $F(1,78) = 42.59$, $p < .001$, $\eta_p^2 = .35$, and at Retention 2, $F(1,78) = 11.53$, $p < .001$, $\eta_p^2 = .13$.

Discussion

Most importantly, Experiment 1b revealed a significant interaction between distractor type and time of distraction, which reflects the fact that the changing-state effect was not significant when the distractors were played at Encoding 1, most pronounced when they were played at Encoding 2 and Retention 1, and somewhat decreased when they were played at

Retention 2. This provides first direct evidence for the assumption of Macken et al. (1999) that the changing-state effect increases with the burden on rehearsal, given that their study design, without a steady-state condition, did not allow testing this directly.

It should be noted that—while the data of Experiment 1a and 1b showed a robust and consistent ordinal pattern across time of distraction with respect to the changing-state conditions —the steady-state condition showed a somewhat noisier pattern. To illustrate, while performance in the steady-state condition followed a similar pattern across both experiments at Encoding 1, Encoding 2 and Retention 2, performance differed between experiments at Retention 1, wich resulted in a different ordering in Experiment 1a (Encoding 1 > Encoding 2 > Retention 1 < Retention 2) in comparison to Experiment 1b (Encoding 1 > Encoding 2 < Retention 1 > Retention 2) when conditions were ranked according to performance. Given that the steady-state conditions did not substantially differ between experiments, this inconsistency may be attributed to random variation in the data. The best way to reduce random influences is to base the analysis on more data. Even though our experiments already had larger sample sizes than previous studies (N = 90 in Experiment 1 and N = 79 in Experiment 2 compared to N = 52 in the study of Macken et al., 1999, and N = 26 in Experiment 1 and N = 29 in Experiment 2 in the study of Hughes et al., 2005), an even larger sample size seems desirable to obtain clearer results. Following the examples of other researchers using this paradigm (Hughes et al., 2005; Vachon, Labonté, & Marsh, 2017), we combined the data of both experiments in a cross-experimental analysis while including the between-subject variable experiment (Experiment 1a, Experiment 1b). Analyzing the data in this way seems reasonable given that the procedure was identical except for the distractor material used. It also seems reasonable to have more confidence in results that are based on a total of $N = 169$ participants than on results that are based on much smaller sample sizes.

Figure 2 displays the mean serial recall performance in the steady-state condition and in the changing-state condition as a function of time of distraction. Recall was better in the steady-state than in the changing-state condition, $F(1,167) = 87.08$, $p < .001$, $\eta_p^2 = .34$, and differed as a function of time of distraction, $F(3,165) = 51.36$, $p < .001$, $\eta_p^2 = .48$. Moreover, performance did not differ as a function of the experiment $F(1,167) = 0.45$ $p = .50$, $\eta_p^2 < .01$, and the experiment variable did not interact with distractor condition $F(1,167) = 2.22$ $p = .14$, $\eta_p^2 = .01$, or time of distraction $F(3,165) = 1.75$, $p = .16$, $\eta_p^2 = .03$. Importantly, a significant interaction between auditory distractor type and time of distraction, $F(3,165) = 3.16$, $p = .03$, $\eta_p^2 = .05$, confirmed that the changing-state effect varied as a function of time of distraction. The smallest changing-state effect was obtained when the distractors were played at Encoding 1, $F(1,168) = 9.47$, $p < .01$, $\eta_p^2 = .05$. The largest changing-state effect was obtained when the distractors were played at Encoding 2, $F(1,168) = 45.02$, $p < .001$, $\eta_p^2 = .21$. Playing the distractors at Retention 1 still produced a considerable amount of distraction, $F(1,168) = 31.65$, $p < .001$, $\eta_p^2 = .16$. Playing the distractors at Retention 2 led to a significant, but somewhat smaller, changing-state effect, $F(1,168) = 14.95$, $p < .001$, $\eta_p^2 = .08$. The tree-way interaction between distractor type, time of distraction and experiment was also significant $F(3,165) = 3.72$, $p = .03$, $\eta_p^2 = .05$, which can be attributed to the fact that the interaction between auditory distractor type and time of distraction was not significant in Experiment 1a ($p = .06$) but obtained significance in Experiment 1b ($p < .01$). Taken together, the pattern of results seems consistent with the prediction of the duplex account that the changing-state effect increases with the burden on serial rehearsal. However, the finding that performance is similarly affected by time of distraction in the steady-state condition, $F(3,166) = 9.69$, $p < .001$, $\eta_p^2 = .15$, and in the changing-state condition, $F(3,166) = 35.58$, $p < .001$, $\eta_p^2 = .39$ (Figure 2), suggests that this pattern could be due to a more general distraction effect, and not specific to changing-state distraction. Experiments 2a and 2b serve to test whether this pattern generalizes to the disruption of serial recall by auditory deviations.

Is the deviation effect influenced by time of distraction?

To explain that both the changing-state and the steady-state condition were affected by time of distraction in Experiments 1a and 1b, one may postulate (1) that the steady-state distractors captured some amount of attention, and (2) that attention capture interferes with the rehearsal of the target items. To test this attentional explanation directly, it is necessary to examine how the deviation effect is modulated by time of distraction. In contrast to the changing-state effect, the deviation effect is widely accepted to be due to attentional capture (Hughes et al., 2007; Parmentier, 2016; Röer, Bell, & Buchner, 2014; Vachon et al., 2012). The influence of time of distraction was tested by presenting auditory deviants during the same four time intervals that were used to manipulate time of distraction in the two previous experiments. The duplex account (Hughes et al., 2007, 2013; Jones et al., 2010) implies that the deviation effect is caused by an attentional disruption of the encoding of the target items while the serial rehearsal process remains unaffected by attentional distraction. Therefore, the account predicts that auditory deviants only affect serial recall when they are presented at Encoding 1 or at Encoding 2, but not when they are presented at Retention 1 or at Retention 2. According to the embedded-processes model (Cowan, 1995), in contrast, the changing-state effect and the deviation effect are caused by similar mechanisms. Specifically, the model implies that the encoding and rehearsal of the target material require the focus of attention, which is captured by changing and deviant distractor stimuli. Therefore, the model predicts that the results of Experiment 2a should be parallel to the results of Experiments 1a and 1b. Specifically, deviant distractors should have only a small effect when presented at Encoding 1 and should cause most distraction when presented at Encoding 2. In contrast to the duplex account, the embedded-processes model predicts that retention is disrupted by the deviants as well.

In Experiments 2a and 2b, the deviants were presented after a large number of steady-state standard stimuli, irrespective of the time interval in which the deviants were presented. The purpose of this procedure was to guarantee that participants had ample opportunity to form a neural model of the standard steady-state stimulus before the deviant occurred, which is a prerequisite for observing a well-defined capture effect. One consequence of this procedure is that it was necessary to present the standard steady-state stimuli throughout the whole trial (before and after the deviant was presented) to avoid confounding time of distraction with the amount of standard steady-state distractors that had to be ignored during the trial. Hence, time of distraction refers only to the deviants and not to the steady-state distractors that were presented throughout the whole encoding interval and the whole retention interval in Experiments 2a and 2b, regardless of distractor condition.

Experiment 2a

Method

Participants. One hundred and two students (67 women) at Heinrich Heine University Düsseldorf aged 19 to 39 years (M = 24) participated in exchange for course credit or a small honorarium. All reported normal hearing and normal or corrected-to-normal vision and were fluent German speakers.

Materials, Procedure, and Design. Materials, procedure, and design were identical to those of Experiments 1a and 1b with the following exceptions. Auditory distractors consisted of 32 different deviant sequences and 32 steady-state sequences. The to-be-ignored words were selected from the set of eight one-syllable German nouns used in Experiment 1a. In the deviant condition, a sequence of identical steady-state distractor repetitions was disrupted by a deviant distractor word. The deviant could be presented at any position at Encoding 1, Encoding 2, Retention 1, or Retention 2. Within each interval, eight distractors were presented. Thus, there were eight distractor positions in each of the four time intervals in which a deviant could be presented. In each of the 32 deviation trials, the deviant was presented at a different position within one of the four time intervals. Each trial started with a 15.5 second pre-encoding interval. The onset of the steady-state sequence within the pre-encoding interval depended on the position of the deviant in the to-be-ignored distractor sequence to guarantee that, independent of its position, each deviant was preceded by 31 steady-state distractor repetitions (see Figure 3). This procedure ensured that participants had the same opportunity to build up a neural model of the standard steady-state stimulus prior to the presentation of the deviant stimulus, independent of the position of the deviant stimulus in the sequence. To avoid confounding time of distraction with the number of steady-state distractors that had to be ignored at encoding or retention, the steady-state sequence continued throughout the whole presentation interval and the whole retention interval until the recall cue was presented. For each deviant sequence, there was a steady-state control sequence that was identical to the deviation sequence with the only exception that the deviant was replaced by a standard steady-state distractor. Each of the eight distractor words of the word set was selected four times for presentation as the standard steady-state word in each condition. In the deviant condition, another word from the word set was randomly drawn to be used as the deviant.

Given a total sample size of $N = 102$, $\alpha = .05$, and $\rho = .30$, an interaction between distractor type and time of distraction of size $f = .18$ could be detected with a probability of $1 - \beta = .95$.

Results

Table 1 shows the mean serial recall performance in the deviant condition and in the steady-state control condition, as well as the differences between conditions, as a function of time of distraction. A 2 × 4 repeated-measures MANOVA showed a typical deviation effect: serial recall was impaired by auditory deviants relative to the steady-state control condition, $F(1,101) = 12.23$, $p < .01$, $\eta_p^2 = .11$. Performance varied as a function of time of distraction, $F(3,99) = 3.76$, $p = .01$, $\eta_p^2 = .10$. The interaction between distractor type and time of distraction just missed the conventional level of statistical significance, $F(3,99) = 2.58$, $p = .06$, $\eta_p^2 = .07$. The deviation effect was not significant when the deviant was played at Encoding 1, $F(1,101) = .16$, $p = .69$, $\eta_p^2 < .01$, but it was significant when the deviant was played at Encoding 2, $F(1,101) = 7.44$, $p < .01$, $\eta_p^2 = .07$, and at Retention 1, $F(1,101) = 11.38$, $p < .01$, $\eta_p^2 = .10$. When the deviant was played at Retention 2, the deviation effect was not significant, $F(1,101) = .74$, $p = .39$, $\eta_p^2 < .01$.

Discussion

As in Experiment 1a, the interaction between distractor type and time of distraction was not significant. This is inconsistent with the prediction of the duplex-mechanism account

(Hughes et al., 2007, 2013; Jones et al., 2010) that the auditory deviants affect only encoding, but not retention. However, the interaction again just failed to reach the conventional level of statistical significance. The descriptive pattern of results was also very similar to Experiment 1a: the deviation effect was smallest (and failed to reach significance) when the distractors were played at Encoding 1; the deviation effect was more pronounced, and statistically significant, when the deviants were played at Encoding 2 and at Retention 1; the deviation effect was less pronounced, and not statistically significant, when the deviants were played at Retention 2. Before rejecting the idea that the deviation effect varies as a function of time of distraction, we decided to collect more data in Experiment 2b, and to combine the data of both experiments to see whether the interaction between distractor type and time of distraction would be observed in a test with higher statistical power, parallel to the cross-experimental analysis of Experiments 1a and 1b.

Experiment 2b

Deviants are assumed to disrupt cognitive tasks due to the violation of expectations that are based on regularities in the auditory environment (Nöstl, Marsh, & Sörqvist, 2012, 2014; Röer et al., 2014; Vachon et al., 2012). In Experiment 2a, deviants were presented in half of the trials. It is possible to speculate that this high percentage of deviation trials may have reduced the degree to which the deviants violated expectations at a global level (within the whole experiment), and, consequently, the disruptive potential of the deviants. In Experiment 2b, we used a smaller number of deviant trials to make the occurrence of the deviant less predictable. Although it has been shown that deviations within a trial are most potent in determining attentional capture (Röer et al., 2014), there are also reports that deviations across trials may capture attention (Röer et al., 2011; Vachon et al., 2012). A priori, it seemed conceivable that rare deviants may cause a larger deviation effect, which could facilitate finding a modulation of this effect by time of distraction.

Method

Participants. One hundred and twenty-three students (83 women) at Heinrich Heine University Düsseldorf aged 18 to 39 years (M = 23) participated in exchange for course credit or a small honorarium. All reported normal hearing and normal or corrected-to-normal vision and were fluent German speakers.

Materials, Procedure, and Design. Materials, procedure, and design were identical to those of Experiment 2a with the following exceptions. Only 16 deviant trials were intermixed with 48 steady-state control trials. As in Experiment 2a, the deviants could occur either at Encoding 1, Encoding 2, Retention 1, or Retention 2. More precisely, the deviants always occurred on Positions 3, 4, 5, or 6 within each time interval. Each trial started with a 13.5-second pre-encoding interval before the first target digit was shown. Independent of the position of the deviant (or the time interval it was presented in), each deviant was preceded by a sequence of 29 standard steady-state distractors. Given that there were three times as many steady-state trials as deviant trials, each deviant trial was matched with three steady-state control trials.

Given a total sample size of $N = 123$, $\alpha = .05$, and $\rho = .30$, an interaction between the auditory distractor condition and the presentation block variable of size $f = .16$ could be detected with a probability of $1 - \beta = .95$.

Results

Table 1 shows the mean serial recall performance in the deviant condition and in the steady-state control condition, as well as the differences between conditions, as a function of time of distraction. A 2 × 4 repeated-measures MANOVA confirmed that there was a typical deviation effect, $F(1,122) = 29.08$, $p < .001$, $\eta_p^2 = .19$. Performance did not differ as a function of time of distraction, $F(3,120) = 1.77$, $p = .16$, $\eta_p^2 = .04$, but there was a significant interaction between distractor type and time of distraction, $F(3,120) = 3.77$, $p = .01$, $\eta_p^2 = .09$. A small deviation effect was observed when the deviant was played at Encoding 1, $F(1,122) = 5.13$, $p = .03$, $\eta_p^2 = .04$. The largest deviation effect was obtained when the deviant occurred at Encoding 2, $F(1,122) = 27.42$, $p < .001$, $\eta_p^2 = .18$. There was no deviation effect when the deviant was presented at Retention 1, $F(1,122) = 0.35$, $p = .56$, $\eta_p^2 < .01$, but there was a small effect when the deviant was presented at Retention 2, $F(1,122) = 6.48$, $p = .01$, $\eta_p^2 = .05$.

Discussion

In Experiment 2b, the deviation effect was most pronounced at Encoding 2, parallel to the distraction effects in all other experiments. However, there were also inconsistencies across Experiments 2a and 2b. Similar to the changing-state condition in Experiment 1a and 1b, the deviation condition in Experiment 2a and 2b showed a consistent and robust ordinal pattern when the time intervals were ranked according to performance. In the steady-state condition, however, performance at Retention 1 behaved inconsistently. It was better than Encoding 2 and Retention 2 in Experiment 2a but worse than the adjacent time-of-presentation blocks in Experiment 2b. Given that the steady-state distractors were played during the whole presentation phase and the whole retention phase, this inconsistency may be attributed to random variation in the data. The best way to reduce unsystematic influences is to base the analysis on more data. Even though sample sizes were much larger in the present Experiments 2a and 2b (*N* = 102 and

N = 123, respectively) than in previous studies, it seems desirable to base the conclusions on an even larger sample size. Given that the procedure of Experiments 2a and 2b were nearly identical except for the frequency of distractors, it seems reasonable to analyze the data of Experiments 2a and 2b in a cross-experimental analysis with a total sample size *N* = 225. Again, it seems also reasonable to place more trust in results that are based on a larger sample.

Figure 4 shows serial recall in the steady-state control condition and in the deviant condition as a function of time of distraction. Serial recall was better in the steady-state condition than in the deviant condition, $F(1,223) = 38.63$, $p < .001$, $\eta_p^2 = .15$, and differed as a function of time of distraction, $F(3,221) = 4.61$, $p < .01$, $\eta_p^2 = .06$. There was no main effect of experiment, $F(1,223) = 0.12$, $p = .74$, $\eta_p^2 < .01$, and experiment did not interact with distractor condition $F(1,223) = 1.08$, $p = .30$, $\eta_p^2 < .01$, nor did it interact with time of distraction $F(3,221) = 1.04$, $p = .38$, $\eta_p^2 = .01$. Importantly, the significant interaction between distractor type and time of distraction, $F(3,221) = 2.95$, $p = .03$, $\eta_p^2 = .04$, confirms that the deviation effect varies as a function of time of distraction. The smallest deviation effect was found when the deviants were played at Encoding 1, $F(1,224) = 4.32$, $p = .04$, $\eta_p^2 = .02$. The largest deviation effect was obtained when the deviants occurred at Encoding 2, $F(1,224) = 31.92$, $p < .001$, $\eta_p^2 = .12$. Playing the deviants at Retention 1 caused a significant disruption of serial recall, $F(1,224) = 6.25$, $p = .01$, $\eta_p^2 = .03$, as did playing the deviants at Retention 2, $F(1,224) = 6.41$, $p = .01$, $\eta_p^2 = .03$. As in the combined analysis of Experiments 1a and 1b, the three-way interaction just reached significance, $F(3,221) = 2.66$, $p = .05$, $\eta_p^2 = .04$, reflecting the fact that the interaction between auditory distractor type and time of distraction was not significant in Experiment 2a ($p = .06$) but obtained significance in Experiment 2b ($p = .01$).

This pattern of results is very similar to that obtained in Experiments 1a and 1b, and suggests that both changing-state and deviant distractors interfere with rehearsal. The results are inconsistent with the assumption of the duplex account (Hughes et al., 2007, 2013; Jones et al., 2010) that attention capture only interferes with the encoding, but not with the retention of the target items. Note, however that the size of the deviation effect is generally smaller (η_p^2 = .15 in the combined analysis of Experiments 2a and 2b) than the size of the changing-state effect (η_p^2 = .34 in the combined analysis of Experiments 1a and 1b). This is consistent with the present literature (e.g., Hughes et al., 2013; Hughes et al., 2005; Röer, Bell, Marsh, et al., 2015; Sörqvist, 2010), and to be expected because deviant distractors occur much less frequently, and thus have less opportunity to interfere with serial recall than changing-state distractors. As a consequence, it is unsurprising that a deviation effect during retention (η_p^2 = .03 and η_p^2 = .03 at Retention 1 and 2 in the combined analysis of Experiments 2a and 2b) is missed more easily than the changing-state effect (η_p^2 = .16 and η_p^2 = .08 during Retention 1 and 2, respectively, in the combined analysis of Experiments 1a and 1b) when the statistical conclusions are based on small sample sizes.

General Discussion

The present study tested which time intervals during a serial recall task are most sensitive to auditory distraction. Experiments 1a and 1b combined extend the findings of Macken et al. (1999) by confirming that the changing-state effect is modulated by time of distraction, as predicted by the duplex account (Hughes et al., 2007; 2013; Jones et al., 2010). However, the results of Experiments 2a and 2b show that this characteristic pattern is not specific for changing-state distraction. Just as the changing-state effect, the deviation effect was least pronounced when the deviants were played at Encoding 1 when the task presumably is least demanding, and most pronounced when the deviants were played at Encoding 2 when the task presumably is most demanding (see below). Inconsistent with some earlier results (Hughes et al., 2005), but consistent with others (Röer et al., 2014), deviants continued to disrupt performance when they were presented during target retention (at Retention 1 and 2), which is again parallel to the pattern observed with changing state distractors. These findings suggest that both changing-state and deviant distractors disrupt not only the encoding, but also the rehearsal of the target items.

The least disruption of serial recall was found when the distractors were presented at Encoding 1. Macken et al. (1999) have argued that the burden on rehearsal is low during this time interval because rehearsal load is below span, which may explain why this time interval is relatively insensitive to auditory distraction. Both the changing-state effect and the deviation effect were most pronounced when the distractors were played at Encoding 2. Consistent with these results, Macken et al. (1999) found that presenting irrelevant speech during the second half of item encoding (Encoding 2) resulted in the strongest disruption relative to a quiet control condition (see also Elliott et al., 2016). To explain this finding, Macken et al. proposed that interference increases as a function of rehearsal load. However, if distraction would simply be a linear function of the number of items that have to be rehearsed in working memory, participants should be more distracted when distractors are presented at Retention 1 (when all of the target items have to be rehearsed) than when they are presented at Encoding 2 (when 4 to 8 items have to be rehearsed). The second half of the encoding interval may be particularly susceptible to distraction because rehearsal load is high and participants have to coordinate the ongoing rehearsal of the already-presented target items with the parallel continuous updating of the rehearsal set, which may impose a particularly high burden on working memory resources. Therefore, the effects of auditory distraction do not seem to selectively affect *either* encoding *or* retention. Rather, the amount of distraction seems to be determined by the total amount of resources that are required for encoding *and* retention. Refreshing and updating the rehearsal set at the same time may be particularly challenging. This fits with the general idea that high cognitive load leads to increased susceptibility to distraction (Lavie, 2010; Lavie, Hirst, de Fockert, & Viding, 2004). Serial recall was clearly disrupted by changing and deviant distractors when these were presented during the target retention interval, which suggests that both types of distractors interfere with the retention of the target items. The fact that the deviation effect was not restricted to the encoding of the items suggests that the deviants may interfere with rehearsal, just as the changing-state distractors.

These findings can be explained by the embedded-processes model (Cowan, 1995), which implies that steady-state, changing-state, and deviant distractors capture attention to different degrees. A withdrawal of attention interferes with serial recall because the model implies that focal attention is needed both for the encoding and for the rehearsal of target items within working memory. Specifically, the model assumes that the target items are maintained in working memory by successively bringing them into the focus of attention, which increases the activation of these items in memory (Cowan, 1995), and may serve to support the binding between these items (Bell, Röer, & Buchner, 2013). In consequence, serial recall suffers when auditory distraction interferes with these processes. The model implies that steady-state, changing-state, and deviant distractors may disrupt the same mechanisms to different degrees, leading to the prediction that auditory distraction shows a similar, but differentially pronounced pattern for the different distractor types, and increases with the burden on focal attention imposed by the task. The burden on the focus of attention increases when the amount of to-be-maintained items exceeds what can be simultaneously held in the focus of attention (more than 4 items; Cowan, 2001), and increases from the first half to the second half of the encoding interval. Accordingly, the combined analyses of Experiments 1a and 1b and of Experiments 2a and 2b showed that both the changing-state effect and the deviation effect were small when the burden on working memory was low (at Encoding 1), and comparatively large when the burden on working memory was high (at Encoding 2). Furthermore, the embedded-processes model implies that the rehearsal of items in working memory requires attention, leading to the prediction that the deviation effect is not constrained to the encoding of items, which was confirmed by the finding that deviants disrupted serial recall even when they were played during the retention interval.

The duplex account (Hughes et al., 2007, 2013; Jones et al., 2010), in contrast, predicts that (1) steady-state distractors do not interfere with serial rehearsal because they do not give rise to order processing and should not cause a characteristic pattern of interference when presented at different time intervals during the encoding and retention of target items. This assumption was disconfirmed by the results of Experiments 1a and 1b.[3] The duplex account furthermore predicts (2) that changing-state distractors (in contrast to steady-state and deviant distractors) interfere

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[3] Note that in Experiments 2a and 2b, a continuous stream of steady-state distractors was presented throughout each steady-state trial, which implies that no time-of-distraction effects can be expected.

with target rehearsal, which should result in an increased changing-state effect when the demand on rehearsal is high, that is, at Encoding 2 and at Retention 1. Indeed, the combined analysis of Experiments 1a and 1b showed that interference increased with rehearsal load. Note, however, that disruption was most pronounced when the distractors were presented at Encoding 2 (*before* the presentation of the target set was fully completed and thus *before* rehearsal load should have been at its maximum), but was less pronounced at Retention 1 (when rehearsal load should have been at its maximum because presentation of the target set was fully completed). This is more compatible with the assumption that distraction is a function of general task difficulty rather than rehearsal load alone. Finally, the duplex account (Hughes et al., 2007; 2013; Jones et al., 2010) predicts that (3) deviants are differentially affected by the time of distraction manipulation because they disrupt the encoding of new items (which is assumed to depend on attentional resources), but not the seriation of the target items (which is assumed to be automatic), leading to the prediction that deviants should disrupt performance when played during target encoding, but not when played during target retention. Inconsistent with this prediction, deviation effects were obtained when the deviants occurred in the retention interval. In a recent modification of the duplex account (Hughes, 2014), the hypothesis that the deviation effect should be abolished during the retention interval was maintained, but a different explanation was offered: it was assumed that increasing rehearsal load induces higher task engagement, which in turn shields against the distraction by auditory deviants. Finding that the deviation effect is most pronounced when working memory load is highest (at Encoding 2) is therefore also inconsistent with this revised explanation.

To incorporate the present results, it would be necessary to modify the duplex-mechanism account. One obvious possibility is to allow focal attention to play a role in the seriation of the target items by assuming that establishing and maintaining the order cues that are necessary to serially recall the visually presented items require focal attention, and that these processes are therefore impaired when attention is drawn away from the to-be-recalled stream of items. According to this modified account, the deviants would interfere with the rehearsal of the target items as well, just as the changing-state items. The changing-state effect would then interfere with the same processes as the deviation effect, but for a different reason: The changes in the auditory modality may give rise to order processing, which may interfere with the seriation of the target items in addition to the attentional effects. This revised model would blur the clear distinction between attentional and nonattentional processes that is central to the duplex account (Hughes et al., 2007; 2013; Jones et al., 2010), but the assumption that attentional and interference-based processes are not completely separate and distinct from each other may open new research avenues for examining how the attentional and nonattentional processes interact and influence each other.

In summary, the present study serves to test conflicting predictions about the time intervals in a serial recall task that are most sensitive to different types of auditory distraction. The results suggest that the changing-state effect and the deviation effect are similarly affected by time of distraction, and increase as a function of the burden the primary task places on working memory, suggesting that both types of distraction interfere with basic working memory processes and, thus, are more similar than previously thought.

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Tables

Table 1. Descriptive statistics and difference measures for the proportion of correct responses as a function of distractor type and time of distraction in Experiment 1a, Experiment 1b, Experiment 2a and Experiment 2b.

	Time 1		*Time 2*		*Time 3*		*Time 4*	
	M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Experiment 1a								
Steady-State	0.71	0.02	0.67	0.02	0.66	0.02	0.68	0.02
Changing-State	0.68	0.02	0.61	0.02	0.63	0.02	0.66	0.02
Difference	0.02		0.06		0.03		0.02	
Experiment 1b								
Steady-State	0.70	0.02	0.65	0.02	0.68	0.02	0.67	0.02
Changing-State	0.68	0.02	0.58	0.02	0.60	0.02	0.62	0.02
Difference	0.01		0.07		0.08		0.05	
Experiment 2a								
Steady-State	0.71	0.02	0.71	0.02	0.73	0.02	0.70	0.02
Deviant	0.71	0.02	0.68	0.02	0.69	0.02	0.69	0.02
Difference	0		0.02		0.04		0.01	
Experiment 2b								
Steady-State	0.71	0.01	0.72	0.02	0.70	0.02	0.71	0.01
Deviant	0.69	0.02	0.66	0.02	0.69	0.02	0.68	0.02
Difference	0.02		0.05		0.01		0.02	

Figures

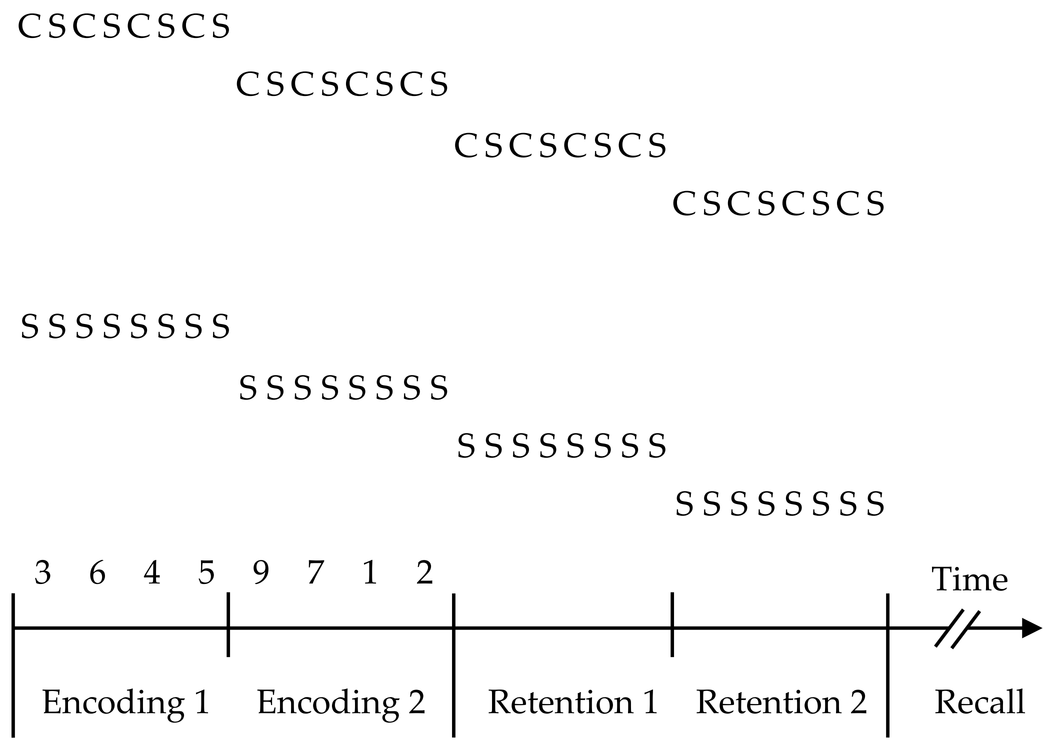

Figure 1. Schematic illustration of the trials in Experiment 1a. Rows of letters depict single trials in which the changing-state (C S C S C S C S) and steady-state (S S S S S S S S) sequences were either presented during the first half of the encoding interval (Encoding 1, first row),during the second half of the encoding interval (Encoding 2, second row), during the first half of the retention interval (Retention 1, third row), or during the second half of the retention interval (Retention 2, forth row). Each letter represents a single distractor word in the changing-state or steady-state condition.

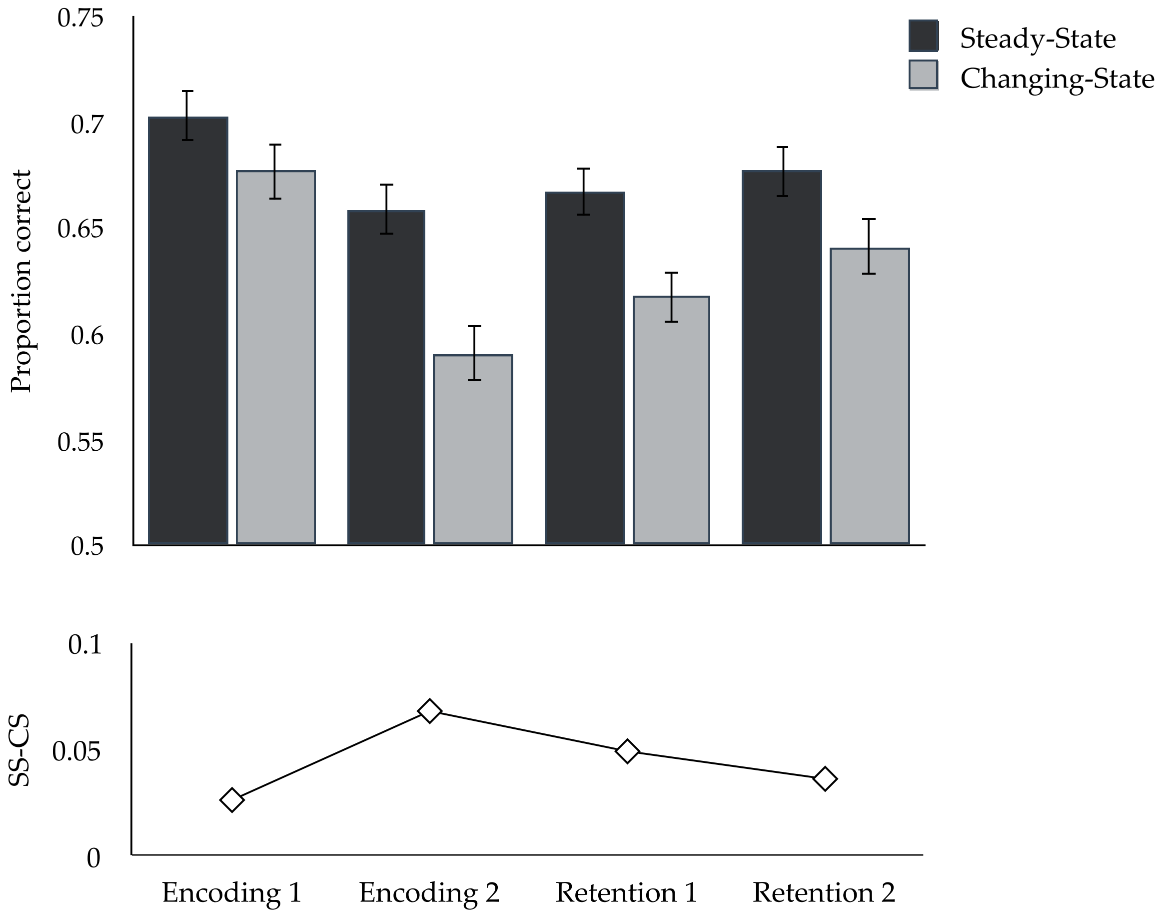

Figure 2. The upper panel displays the proportion of correct responses as a function of distractor type and time of distraction in the combined analysis of Experiment 1a and 1b. The lower panel shows the performance differences between the steady-state and the changing-state condition (steady-state - changing-state) as a function of time of distraction. The error bars depict the standard error of means.

Figure 3. Schematic illustration of four deviant and four steady-state trials in Experiment 2a. Rows depict example trials and each letter represents a single distractor words in the deviant (S S S D S…) and the steady-state (S S S S S…) control condition. Four exemplary deviant trials are presented, in which the deviant is presented in the first half of the encoding interval (Encoding 1, first row), in the second half of the encoding interval (Encoding 2; second row), in the first half of the retention interval (Retention 1, third row) and the second half of the retention interval (Retention 2, fourth row). The deviants could occur at any of the eight distractor positions in each of the four time intervals, but are exemplary presented at the fifth position within each interval in this Figure. Each trial started with a 15,5 second pre-encoding interval. The onset of the steady-state sequence within the pre-encoding interval depended on the position of the deviant in the to-be-ignored distractor sequence to guarantee that, independent of its position, each deviant was preceded by a train of 31 steady-state distractors.

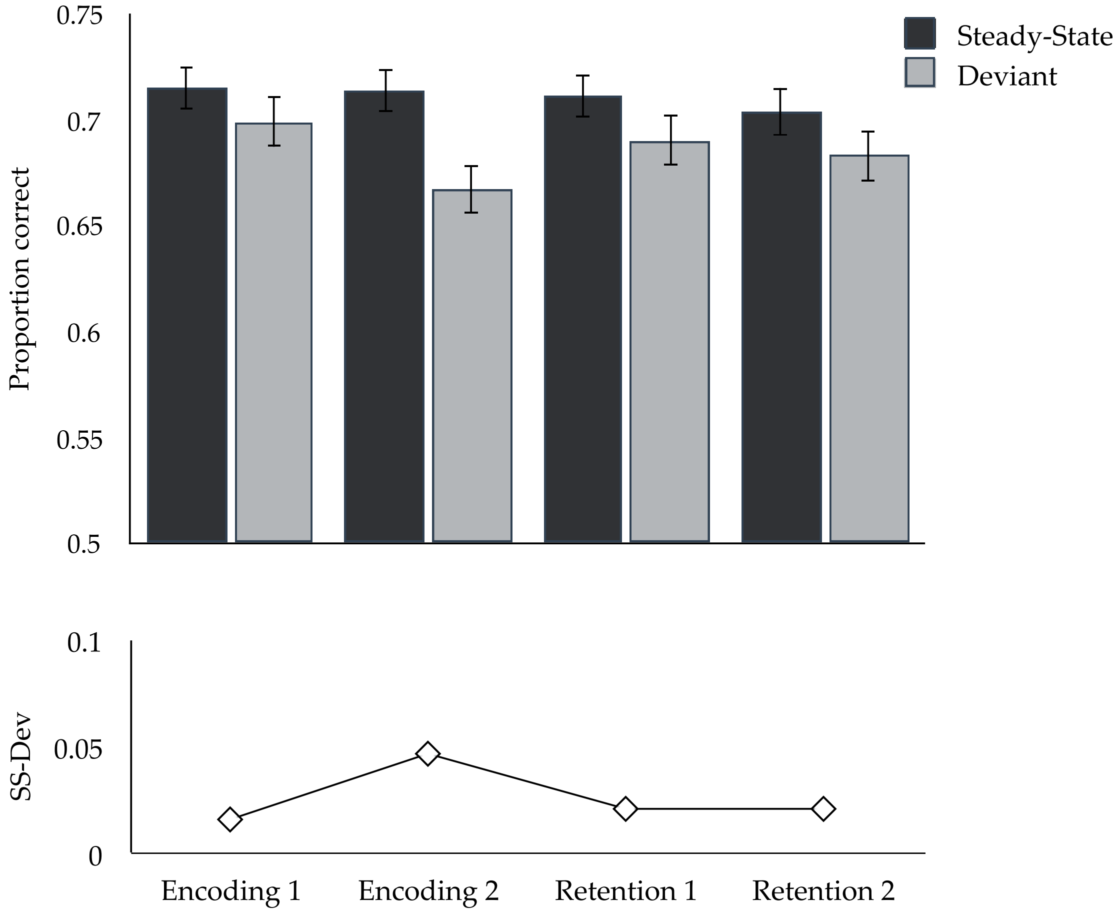

Figure 4. The upper panel displays the proportion of correct responses as a function of distractor type and time of distraction in the combined analysis of Experiment 2a and 2b. The lower panel shows the performance differences between the steady-state and the deviant condition (steady-state - deviant) as a function of time of distraction. The error bars depict the standard error of means.

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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.

Introduction

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

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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. A A A A A A A A) 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. A A A A B A A A).

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), Elliott 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 (Parmentier & Hebrero, 2013). 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, nonwords, or tones) does not correlate with WMC (Beaman, 2004; Elliott & Briganti, 2012; Sörqvist, 2010; Sörqvist et al., 2013), the hypothesis of a negative relationship between the deviation effect and WMC can be challenged for several reasons. Due to the grater involvement of attention, the deviation effect, in contrast, should be more open to top-down cognitive control than the changing-state effect. 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 $p = 0.04$) while the other just falls short of significance (e.g., with $p = 0.06$) 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, $z = 1.55$, $p = 0.06$.[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 0.06 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.

Experiment 1

Method

Participants

A total of 138 students at Heinrich Heine University Düsseldorf (95 women) with a mean age of 24 years ($SD = 4.88$) 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 $\{1, 2, \ldots, 9\}$. 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

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

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 min.

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 $\alpha = 0.05$, it was possible to detect a correlation of $\rho = -0.40$ (between changing-state or deviation distraction and WMC) with a statistical power of $1 - \beta > 0.99$ 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, $r = 0.60$, $p < 0.001$, 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, $F(1,137) = 144.76$, $p < 0.001$, $\eta_p^2 = 0.51$, and by the deviation distractor sequences compared to the steady-state distractor sequences in the deviation block, $F(1,137) = 13.18$, $p < 0.001$, $\eta_p^2 = 0.09$ (see Fig. 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 ($M = 0.09$, $SD = 0.09$) and the deviation effect ($M = 0.02$, $SD = 0.07$) correlated significantly with each other, $r = 0.28$, $p < 0.01$. This could arguably point to the fact that both measures may reflect, in part, the same construct.

We also conducted reliability analysis for our difference scores, following the procedure of Elliott 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 $\alpha = 0.62$ for the changing-state effect and $\alpha = 0.30$ 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 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, $r = 0.04$, $p = 0.67$ (see upper panel of Fig. 2), but WMC did not correlate significantly with the deviation effect either, $r = -0.01$, $p = 0.45$ (see lower panel of Fig. 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 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'* $t(135) = 0.48$, $p = 0.32$.

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 and 10 are commonly

[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., 2005, 2013; 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.

[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.

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

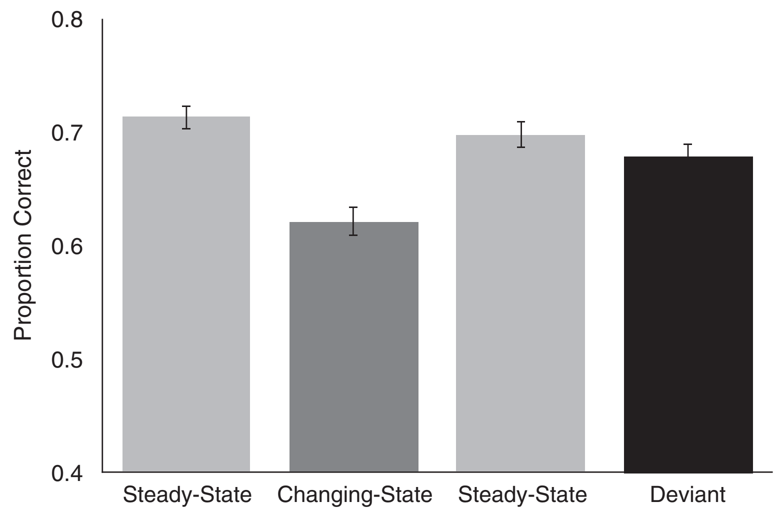

Fig. 1. Proportion of correct responses in the serial recall task of Experiment 1 as a function of distractor type in the changing-state block (steady-state vs. changing state, left bars) and in the deviation block (steady-state vs. deviation sequences, right bars). The error bars represent the standard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

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 & Cowan, 2005; Elliott et al., 2006). 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 & Cowan, 2005; Elliott et al., 2006; 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 ($R^2 = 0.65$, $F[1,136] = 253.74$, $p < 0.001$). However, entering the WMC score in the second step did not lead to a significant increase in the amount of explained variance ($\Delta R^2 < 0.01$, $\Delta F[1,135] = 0.20$, $p = 0.65$). 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 ($R^2 = 0.78$, $F[1,136] = 485.02$, $p < 0.001$). Entering the WMC score in the second step did not lead to a significant increase in the amount of explained variance ($\Delta R^2 < 0.01$, $\Delta F[1,135] = 1.88$, $p = 0.17$), 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 Elliott 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

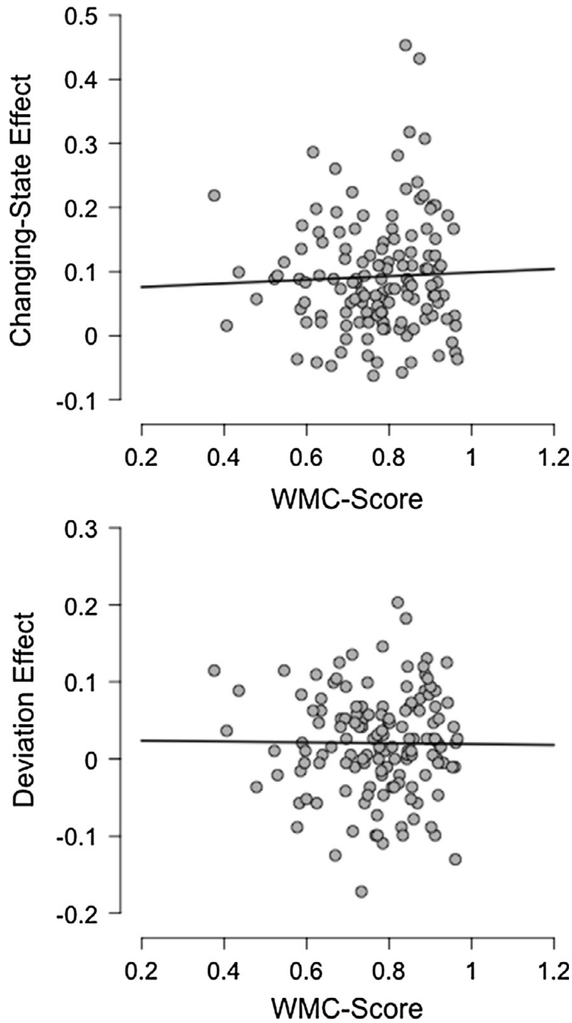

Fig. 2. The correlation between the WMC score and the changing-state effect (calculated as the difference between the serial recall performance in the steady-state and the changing-state condition, upper panel) and the correlation between the WMC score and the deviation effect (calculated as the difference 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).

indeed higher ($\alpha = 0.86$ for the changing-state effect and $\alpha = 0.82$ 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 9 s, 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 min.

Power analysis

Given a total sample size of $N = 63$ and $\alpha = 0.05$, it was possible to detect a correlation of $\rho = -0.40$ (between changing-state or deviation distraction and WMC) with a statistical power of $1 - \beta = 0.95$ 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 $r = 0.71$ for the operation span task and $r = 0.66$ 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, $r = 0.76$, $p < 0.001$. 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, $F(1,61) = 99.08$, $p < 0.001$, $\eta_p^2 = 0.62$, and by the deviation distractor sequences compared to the steady-state distractor sequences in the deviation block, $F(1,61) = 22.68$, $p < 0.001$, $\eta_p^2 = 0.27$ (see Fig. 3). Frequency of the changing-state or deviation distractors had no main effect on performance in the changing-state block, $F(1,61) = 0.24$, $p = 0.63$, $\eta_p^2 < 0.01$, or in the deviation block, $F(1,61) = 1.50$, $p = 0.23$, $\eta_p^2 = 0.02$, respectively. Even more importantly, frequency did not modulate either the changing-state effect, $F(1,61) = 0.08$, $p = 0.77$, $\eta_p^2 < 0.01$, or the deviation effect, $F(1,61) = 0.17$, $p = 0.68$, $\eta_p^2 < 0.01$.

Difference scores representing the changing-state effect and the deviation effect were calculated as in Experiment 1. The changing-state effect ($M = 0.12$, $SD = 0.10$) and the deviation effect ($M = 0.04$, $SD = 0.07$) did not correlate significantly, $r = 0.09$, $p = 0.49$, 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 ($M = 0.13$, $SD = 0.09$) and the deviation effect ($M = 0.04$, $SD = 0.06$) in the condition with the balanced amount of trials $r = 0.29$, $p = 0.05$. 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 ($M = 0.12$, $SD = 0.10$) and the deviation effect ($M = 0.05$, $SD = 0.08$) did not correlate significantly $r = -0.06$, $p = 0.37$, 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, the reliability was calculated as in Experiment 1, following the procedure of Elliott and Cowan (2005). In this condition Cronbach's alpha was $\alpha = 0.56$ for the changing-state effect and $\alpha = 0.12$ 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 five adjacent steady-state trials (e.g. steady-state trial 1–5, 6–10, 11–15, 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 $\alpha = 0.37$ for the changing-state effect and $\alpha < 0.01$ 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, $r = -0.11$, $p = 0.21$ (see upper panel of Fig. 4). Likewise, no significant correlation was found between WMC and the deviation effect, $r = -0.03$, $p = 0.42$ (see lower panel of Fig. 4).[5] The descriptive tendency is towards a somewhat stronger negative relationship

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

[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.

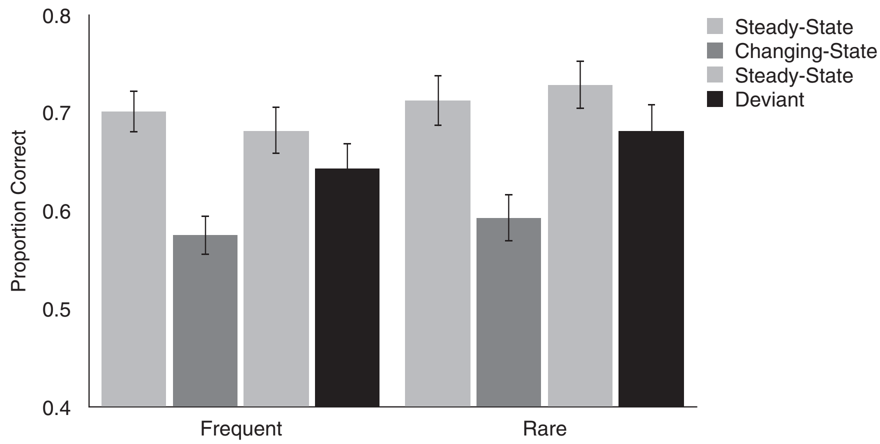

Fig. 3. Proportion of correct responses in the serial recall task of Experiment 2 as a function of frequency (frequent vs. rare) and distractor type in the changing-state block (steady-state vs. changing state) and in the deviation block (steady-state vs. deviation sequences). The error bars represent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

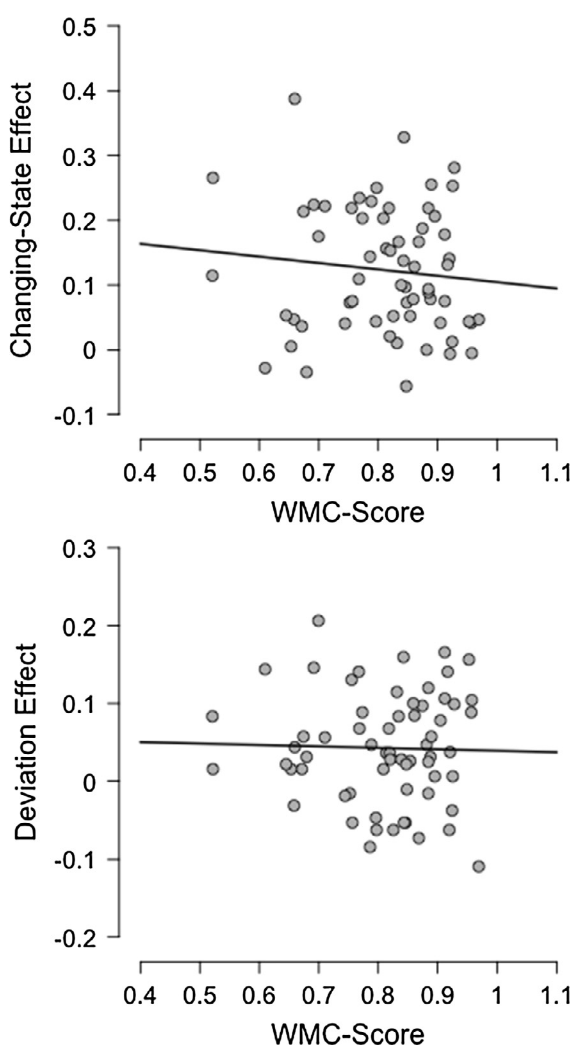

Fig. 4. The correlation between the WMC score and the changing-state effect (calculated as the difference between the serial recall performance in the steady-state and the changing-state condition, upper panel) and the correlation between the WMC score and the deviation effect (calculated as the difference 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).

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, $p = 0.67$.

A supplementary (directional) Bayesian analysis yielded Bayes factors of $BF_{01} = 2.89$ for the correlation between WMC and the changing-state effect and $BF_{01} = 5.35$ for the correlation between WMC and the deviation effect, which indicates that the observed data are 2.89 times (changing-state effect) and 5.35 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 ($R^2 = 0.53$, $F[1,61] = 68.08$, $p < 0.001$), but entering the WMC score in the second step did not lead to a significant increase in the amount of explained variance ($\Delta R^2 = 0.02$, $\Delta F[1,60] = 2.02$, $p = 0.16$), 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 ($R^2 = 0.78$, $F[1,61] = 213.23$, $p < 0.001$), but entering the WMC score in the second step did not lead to a significant increase in the amount of explained variance ($\Delta R^2 < 0.01$, $\Delta F[1,60] = 0.26$, $p = 0.61$), 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 $\alpha = 0.85$ for the changing-state effect and $\alpha = 0.80$ for the deviation effect. In the rare condition, Cronbach's alpha of the residuals was $\alpha = 0.45$ for the changing-state effect and $\alpha = 0.29$ 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 the 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 ($\eta_p^2 = 0.55$) 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 $\alpha = 0.05$, it was possible to detect a correlation of $\rho = -0.40$ (between changing-state or deviation distraction and WMC) with a statistical power of $1 - \beta > 0.99$ 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, $F(1,141) = 148.07$, $p < 0.001$, $\eta_p^2 = 0.51$, and by the deviation distractor sequences compared to the steady-state distractor sequences in the deviation block $F(1,141) = 40.32$, $p < 0.001$, $\eta_p^2 = 0.22$ (see Fig. 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 ($M = 0.10$, $SD = 0.10$) and the deviation effect ($M = 0.05$, $SD = 0.09$) correlated significantly with each other, $r = 0.39$, $p < 0.001$.

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 four adjacent steady-state trials in each block (e.g. steady-state trial 1–4, 5–8, 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 difference scores for the deviation effect, which were then used to calculate Cronbach's alpha. Cronbach's alpha was $\alpha = 0.51$ for the changing-state effect and $\alpha = 0.31$ 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, $r = 0.12$, $p = 0.93$ (see upper panel of Fig. 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, $r = 0.09$, $p = 0.85$ (see lower panel of Fig. 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 the 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'* $t(139) = 0.32$, $p = 0.37$.

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 ($R^2 = 0.63$, $F[1,140] = 234.98$, $p < 0.001$), but entering the operation span score in the second step did not lead to a significant increase in the amount of explained variance ($\Delta R^2 < 0.001$, $\Delta F[1,139] = 0.08$, $p = 0.78$), 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 ($R^2 = 0.71$, $F[1,140] = 334.06$, $p < 0.001$),

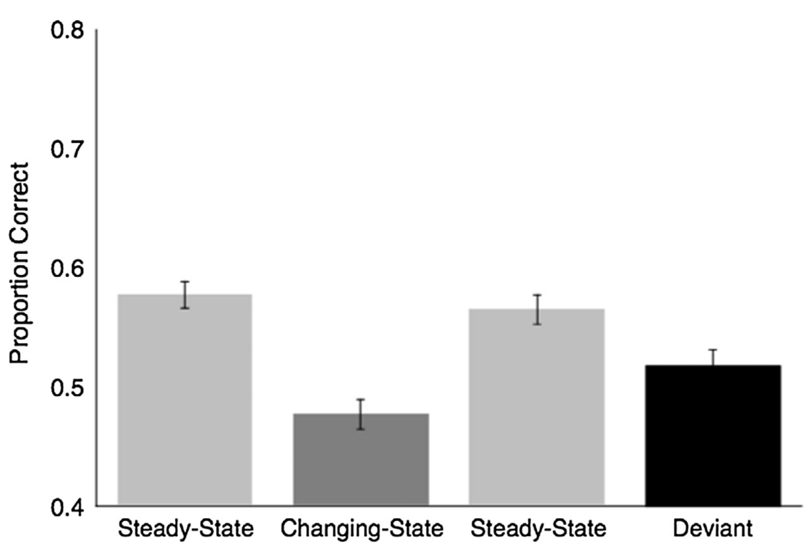

Fig. 5. Proportion of correct responses in the serial recall task of Experiment 3 as a function of distractor type in the changing-state block (steady-state vs. changing state, left bars) and in the deviation block (steady-state vs. deviation sequences, right bars). The error bars represent the standard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

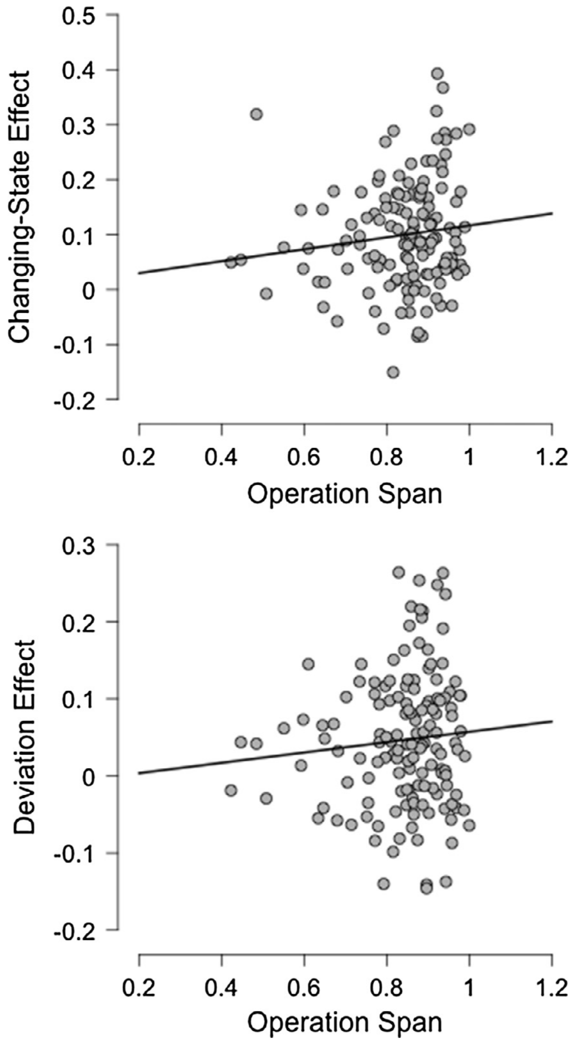

Fig. 6. The correlation between the operation span score and the changing-state effect (calculated as the difference between the serial recall performance in the steady-state and the changing-state condition, upper panel) and the correlation between the operation span score and the deviation effect (calculated 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).

but entering the WMC score in the second step did not lead to a significant increase in the amount of explained variance ($\Delta R^2 < 0.001$, $\Delta F[1,139]$ $p = .03$, $p = 0.87$), 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 $\alpha = 0.60$ for the changing-state effect and $\alpha = 0.48$ 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 ($\eta_p^2 = 0.22$) was similar to that obtained in the present Experiment 2 ($\eta_p^2 = 0.27$), 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 ($F[1,141] = 121.30$, $p < 0.001$, $\eta_p^2 = 0.46$) and the deviation effect ($F[1,141] = 25.39$, $p < 0.001$, $\eta_p^2 = 0.15$) were somewhat smaller than when all four blocks were analyzed ($\eta_p^2 = 0.51$ and $\eta_p^2 = 0.22$ 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 $\alpha = 0.25$ instead of $\alpha = 0.51$ for the changing-state effect and $\alpha = 0.26$ instead of $\alpha = 0.31$ 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, Bell, Marsh 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, Bell, Marsh 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 (Röer, Bell, Marsh et al., 2015; Sörqvist, 2010). 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 Figs. 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, Bell, Marsh 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, Bell, Marsh 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 Fig. 7.

As in the present Experiments 1 and 3, as well as in the condition with the balanced amount of trials in every condition in Experiment 2, there was a significant positive correlation between the changing-state effect ($M = 0.06$, $SD = 0.11$) and the deviation effect

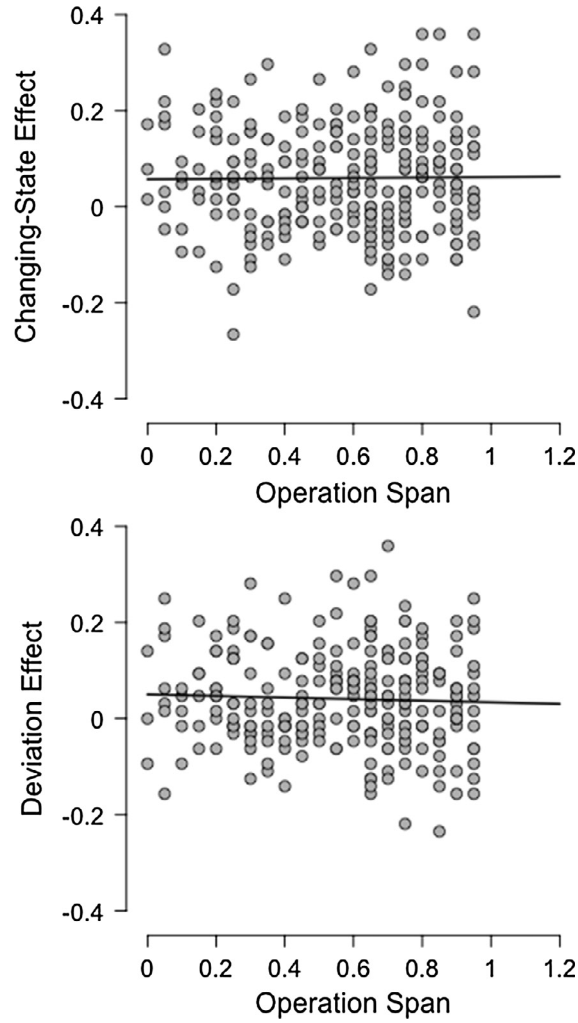

Fig. 7. The correlation between the operation span score and the changing-state effect (calculated as the difference between the serial recall performance in the steady-state and the changing-state condition, upper panel) and the correlation between the operation span score and the deviation effect (calculated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

($M = 0.04$, $SD = 0.10$; $r = 0.36$, $p < 0.001$). Consistent with the present and previous results, the correlation between operation span and the changing-state effect was not significant, $r = 0.01$, $p = 0.57$. The same was true for the correlation between operation span and the deviation effect, $r = -0.04$, $p = 0.25$. When compared directly, the difference between these two correlations was not significant even when tested with a one-sided test, *Williams'* $t(255) = 0.74$, $p = 0.23$. 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 Fig. 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

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

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, Bell, Marsh 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, Bell, Marsh et al.'s (2015) study, this analysis was based on *z*-transformed operation span scores. With a total sample size of $N = 601$ and $\alpha = \beta = 0.05$, a potential correlation as small as $\rho = 0.13$ could be detected, if there was one. However, despite that the power was sufficiently high ($1 - \beta = 0.95$) to detect even a small effect, the operation span scores did not correlate with either the changing-state effect ($r = 0.05$, $p = 0.88$) or the deviation effect ($r = 0.02$; $p = 0.67$). These correlations also did not differ from each other, *Williams*' $t(598) = 0.63$, $p = 0.26$. 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 towards 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 (see Röer et al., 2014b, Röer, Bell, & Buchner, 2015, for detailed 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 witch 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 et al., 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, Bell, Marsh 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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Erklärung über den Eigenanteil an den in der Dissertation enthaltenen Einzelarbeiten

Meine schriftliche Dissertationsschrift umfasst zwei Fachartikel mit insgesamt sieben Experimenten. Im Folgenden ist für jeden der Fachartikel aufgeführt, welche Autoren und Autorinnen bei der Planung der Experimente, bei der Umsetzung der Experimente, bei der Datenauswertung und beim Verfassen der Manuskripte mitgearbeitet haben. Der überwiegende Teil der Arbeit lag jeweils beim Erstautor des Artikels.

Körner, U., Röer, J. P., Buchner, A., & Bell, R. (2017a). Time of presentation affects auditory distraction: Changing-state and deviant sounds disrupt similar working memory processes. *Manuscript submitted for publication*.

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Hiermit versichere ich an Eides Statt, dass ich die Dissertation mit dem Titel „Der Einfluss des Präsentationszeitpunktes und der Arbeitsgedächtniskapazität auf die Störwirkung wechselhafter und devianter auditiver Distraktoren: Ein Modelltest“ selbstständig und ohne unzulässige fremde Hilfe unter Beachtung der „Grundsätze zur Sicherung guter wissenschaftlicher Praxis an der Heinrich-Heine-Universität Düsseldorf“ erstellt habe.
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