The cognitive processing architecture of dual-memory retrieval after practice

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Somewhere, something incredible is waiting to be known.

- *Carl Sagan*

To my parents,

for their unconditional love and support.

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ABSTRACT

Accessing and retrieving information from our memory is a crucial part of our daily lives. However, trying to retrieve multiple information from memory remains a challenge. While research has long focused on human multitasking, and especially dual-tasking, the specific process of dual-memory retrieval is largely unexplored. Dual-memory retrieval refers to the retrieval of two different types of memory information at the same time. However, researchers have proposed capacity constraints in the sense of bottleneck models, that are assumed to hinder humans to retrieve two pieces of information at the same time. Despite these capacity constraints, emerging evidence suggests that humans are indeed able to retrieve two pieces of information at the same time. One candidate model to explain these retrieval processes is the set-cue bottleneck model. Since the model has only been investigated in a small number of studies, the exact mechanisms behind the dual-memory retrieval processes are still under debate. The present work aimed to advance our knowledge on the processing architecture of dual-memory retrieval and to test the predictions of the set-cue bottleneck model by examining new cue-response associations, strategy manipulations as well as distinct age groups. In the course of three studies, this dissertation examined three central factors: task specific factors, explicit strategy instructions and individual factors. With this work I was able to generalize previous findings to a new retrieval context of automatized cue response associations. I was further able to assess the role of strategy instructions and manipulations with respect to the processing architecture. Lastly, I assessed the similarities in the way younger and older adults process dual-memory retrieval. To sum up the main findings, I was capable of examining and supporting the assumptions of the set-cue bottleneck model of dual retrieval and to assess the cognitive processing architecture with respect to the factors that influence differential retrieval processes in human cognition.

PUBLICATIONS INCLUDED

This dissertation is based on the following research articles:

Study 1

Orscheschek*, F., Strobach, T., Schubert, T., & Rickard, T. (2019). Two retrievals from a single cue: A bottleneck persists across episodic and semantic memory. *Quarterly Journal of Experimental Psychology*, *72*(5), 1005-1028. https://doi.org/10.1177/1747021818776818

Study 2

Heidemann, F., Rickard, T. C., Schubert, T., & Strobach, T. (2020). Dual-memory retrieval efficiency after practice: effects of strategy manipulations. *Psychological Research*, *84*(4), 2210-2236. https://doi.org/10.1007/s00426-019-01217-y

Study 3

Heidemann, F., Rickard, T. C., Schubert, T., & Strobach, T. (2022). Age does not modify the processing architecture of dual memory retrieval: an investigation of age-related effects on dual-retrieval practice in younger and older adults. *Aging, Neuropsychology, and Cognition*, *31*(1), 114–144. https://doi.org/10.1080/13825585.2022.2128029

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DEUTSCHE ZUSAMMENFASSUNG

THEORETISCHER HINTERGRUND

Die Untersuchung der Verarbeitungskapazität des menschlichen kognitiven Systems ist seit Jahrzehnten ein zentraler Forschungsschwerpunkt der kognitiven Psychologie. Dabei zeigt sich ein immer größer werdendes Interesse an der Verarbeitung von Multitasking Situationen. Dies liegt vor allem an den wachsenden Anforderungen im Alltag, welcher durch die Konfrontation mit verschiedenen Reizen und durch die Nutzung immer neuer Technologien ein hochkomplexes Netzwerk der Verarbeitung erfordert. In der psychologischen Grundlagenforschung liegt ein spezieller Fokus daher auf der Analyse der kognitiven Leistung in Situationen mit Doppelaufgaben (DA) und den zugrundeliegenden theoretischen Modellen. Bei DA handelt es sich um die simultane Durchführung von zwei unterschiedlichen Aufgaben. Während Einzelaufgaben (EA) bereits Probleme in der Durchführung bereiten können, kommt es in einer DA-Situation zu einer Interferenz zwischen den beiden Aufgaben was die Schwierigkeiten vergrößert (Pashler, 1994; Van Selst & Jolicoeur, 1997). Diese Interferenz kann zu höheren Fehlerraten, sowie längeren Verarbeitungszeiten in DA im Vergleich zu EA führen (Meyer & Kieras, 1997; Pashler, 1994). Diese sogenannten DA-Kosten wurden in diversen Studien mit verschiedenen experimentellen Aufgabentypen beobachtet. Dabei handelte es sich unter anderem um simultane Auswahl-Reaktionszeitaufgaben (Meyer & Kieras, 1997; Pashler, 1994; Van Selst & Jolicoeur, 1997) oder duale Gedächtnisabrufaufgaben (Nino & Rickard, 2003; Rickard & Pashler, 2005; Strobach, Schubert, Pashler, & Rickard, 2014). Ersteres ermöglicht die Untersuchung der DA-Leistungen und der Verarbeitungskapazität vornehmlich im Arbeitsgedächtnis und letzteres vornehmlich im Langzeitgedächtnis.

Studien zu Auswahl-Reaktionszeitaufgaben zeigten, dass Übung die DA-Kosten stark reduzieren kann (Hazeltine, Teague, & Ivry, 2002; Kamienkowski, Pashler, Dehaene, &

Sigman, 2011; Liepelt, Strobach, Frensch, & Schubert, 2011; Ruthruff, Pashler, & Hazeltine, 2003; Ruthruff, Van Selst, Johnston, & Remington, 2006; Schumacher et al., 2001, Strobach, Frensch, Soutschek, & Schubert, 2012). Daraus resultierte eine Anzahl von Hypothesen und theoretischen Erklärungsmodellen, die für eine Reduktion der DA-Kosten mit Übung assoziiert sind (Bherer et al, 2006; Ruthruff et al., 2003; Strobach & Schubert, 2017). Im Gegensatz dazu gibt es nur eine geringe Anzahl von Studien, die sich mit Übungseffekten von DA-Situationen bei Gedächtnisabruf-Aufgaben beschäftigt haben. Daraus folgt, dass kognitive Modelle über Übungseffekte in diesem Bereich deutlich unterentwickelt sind. Jedoch sind Untersuchungen eben dieser Mechanismen essenziell, um zu ermitteln, wie das Langzeitgedächtnis unter hohen Aufgabenanforderungen arbeitet. Dies ist wichtig, da es wahrscheinlich ist, dass andere kognitive Mechanismen in der Verarbeitung von Gedächtnisabrufaufgaben involviert sind, als es bei Wahl-Reaktionszeitaufgaben der Fall ist.

Ein zentrales Ziel dieser Dissertation ist es daher die zugrundeliegende kognitive Verarbeitungsarchitektur von DA bei dualem Gedächtnisabruf zu spezifizieren. Im Folgenden werde ich auf wichtige, grundlegende Vorarbeiten eingehen und aus den daraus resultierenden offenen Fragen die spezifischen Ziele und die im Rahmen dieser Dissertation durchgeführten Studien und Ergebnisse näher erläutern.

Grundlegende Vorarbeiten zum dualen Gedächtnisabruf nach Übung

In den wenigen vorliegenden Studien zu dualem Gedächtnisabruf nach Übung (Nino & Rickard, 2003; Rickard & Pashler, 2005; Strobach et al., 2014) wurde der duale Abruf von zwei Reaktionen von einem Stimulus untersucht. Die Nutzung von nur einem Stimulus, welcher mit zwei verschiedenen Aufgabentypen gekoppelt wird, eliminiert den Prozess zwei Stimuli wahrzunehmen und voneinander unterscheiden zu müssen. Dies verringert die zusätzliche Belastung, die durch die geteilte Aufmerksamkeit zwischen zwei Stimuli entsteht und sorgt damit für eine Verringerung der Interferenz zwischen den Aufgaben (Fagot & Pashler, 1992).

In den Studien von Nino und Rickard (2003) sowie Strobach et al. (2014), wurde die Aufgabe wie folg aufgebaut: Der Stimulus (i.e., das Stichwort) entsprach einem auf dem Computerbildschirm präsentierten Farbwort (z.B. rot) welches mit einer verbalen Aufgabe, sowie mit einer manuellen Tastendruckaufgabe kombiniert wurde. In der Tastendruckaufgabe lernten die Teilnehmer entweder eine linke oder eine rechte Taste entsprechend der Farbwörter zu drücken (z.B. grün → links, blau → rechts, rot → rechts, etc.). In der verbalen Aufgabe lernten die Teilnehmer jeweils eine bestimmte Zahl als Reaktion auf eines der Farbwörter in ein Mikrofon zu sprechen (z.B. grün → „fünf“, blau → „sechs“, rot → „acht“, etc.). Dabei wurden in der Studie von Strobach et al. (2014) insgesamt vierzehn Stichwörter als Stimuli genutzt. Nachdem diese beiden Aufgaben jeweils in EA-Situationen gelernt und im Verlauf einer Stunde extensiv geübt wurden, bestand der zentrale Teil des Experimentes aus der Übung der Aufgaben neben EA-Situationen auch in DA-Situationen. Im Ablauf des Experimentes von Strobach et al. (2014) absolvierten die Teilnehmer im Verlauf von zwei weiteren jeweils einstündigen Sitzungen eine Übung von insgesamt 30 sogenannten Triaden, bestehend aus jeweils drei Aufgaben-Blöcken: Einzel-Tastendruckaufgabe, Einzel-Verbale Aufgabe und die duale Gedächtnisabrufaufgabe. In der letztgenannten Situation (i.e., die DA) wurde nach der Präsentation des Farbwortes sowohl die verbale Reaktion als auch die Tastendruck Reaktion ausgeführt. Dabei wurde den Teilnehmern keine spezifische Instruktion erteilt, wie die DA-Situation durchzuführen ist. Sie bekamen lediglich die Anweisung, die beiden Aufgaben so schnell und so akkurat wie möglich auszuführen. Während in den EA jeweils nur eine Reaktion gegeben werden musste (manuell oder verbal), sollten in der DA beide Reaktionen auf das Farbwort gegeben werden. Während dieser Übung wurde in jedem der drei Blöcke nur die Hälfte, also sieben, der im Vorfeld gelernten vierzehn Farbworte präsentiert. In der letzten Sitzung gab es eine zusätzliche Transferphase aus fünf Triaden, in welcher zusätzlich die übrigen sieben Farbwörter präsentiert wurden (Strobach et al., 2014).

Die Resultate dieser Studie von Strobach et al. (2014) lassen sich am besten durch die separate Analyse von zwei Teilnehmergruppen beschreiben: *Nicht-Gruppierer* und *Gruppierer*. Die *Nicht-Gruppierer* waren dadurch gekennzeichnet, dass sie ein relativ langes Zeitinterval (IRI, engl. „inter response interval"; > 300 ms) zwischen der ersten Reaktionszeit (RZ1) und der zweiten Reaktionszeit (RZ2) in der DA-Situation zeigten. Im Kontrast dazu zeigten die *Gruppierer* relativ kurze IRIs (< 300 ms). Um die beobachteten Daten und die unterschiedlichen Reaktionszeiten analysieren zu können, nutzten die Autoren das sogenannte effizient-sequenzielle Abrufmodell (ES-Modell, engl. „efficient-sequential retrieval model"; Nino & Rickard, 2003). Auf Basis der Reaktionszeiten in EA-Situationen sagt dieses mathematische Modell die Reaktionszeiten in DA-Situationen voraus, welche entstehen, wenn ein Teilnehmer ein sequenzielles Abrufmuster von zwei Reaktionen zeigen würde. Das Modell nimmt an, dass es einen Engpass (d.h. eine Kapazitätsbeschränkung) im kognitiven System bei der Verarbeitung von DA-Situationen an einer Gedächtnisabrufstufe gibt; auf dieser Stufe werden Informationen über die Reaktionen aus dem Gedächtnis abgerufen.

Im Laufe der Analysen wurden die gemessenen Reaktionszeiten mit den Vorhersagen des ES-Modells verglichen. Für die Nicht-Gruppierer befanden sich die gemessenen Reaktionszeiten zu Beginn der Übung über dem Bereich, der vom ES-Modell vorhergesagt wurde. Allerdings sorgte Übung dafür, dass die beobachteten RZ1 und RZ2 Werte sehr nah mit der ES-Vorhersage übereinstimmten. Nicht-Gruppierer zeigten also Reaktionszeitmuster, die konsistent mit Annahmen von sequenziellem Gedächtnisabruf sind. Im Vergleich zu den Vorhersagen des ES-Modells, zeigten auch die Gruppierer zu Beginn der Übung Reaktionszeiten, die über der ES-Vorhersage lagen. Im weiteren Verlauf der Übung fielen ihre Werte jedoch signifikant unter die der Vorhersage. Damit war die ES-Vorhersage für diese Teilnehmer ungültig und sie zeigten keine Reaktionszeitmuster, die konsistent mit der Annahme eines sequenziellen Abrufes sind.

Die beobachteten Ergebnisse können im Rahmen des *set-cue bottleneck Modells* interpretiert werden (Nino & Rickard, 2003). Das set-cue bottleneck Modell des dualen Gedächtnisabrufes besteht aus drei sequenziellen, unabhängigen und additiven Verarbeitungsstufen: Die Wahrnehmungsstufe, die Abrufstufe und die motorische Stufe. Diese Stufen umfassen den Aktivitätsfluss vom Moment der Stimulus Präsentation bis hin zur Ausführung der Reaktion. Das Modell nimmt an, dass ein Engpass auf der Abrufstufe besteht, durch den nur ein Gedächtnisabruf nach dem anderen erfolgen kann.

Es wird angenommen, dass es innerhalb der Abrufstufe, auf der sogenannten set-cue Stufe, einen Alles-oder-Nichts Wettkampf zwischen den einzelnen Reaktionen gibt (Nino & Rickard, 2003). In einer DA-Situation mit sequenziellem Abruf wird hier eine der Reaktionen zuerst aktiviert und leitet den Abrufprozess ein. Erst nachdem die erste Reaktion abgerufen wurde, findet der Abrufprozess der zweiten Reaktion statt. Dieser Prozess reflektiert die Annahmen des Abrufes und des Verarbeitungsprozesses für die Teilnehmer, die als Nicht-Gruppierer klassifiziert wurden. Während auch die Gruppierer am Anfang der Übung einen sequenziellen Abruf zeigen, ändert sich dies nach einigen Übungswiederholungen. Dabei wird angenommen, dass die Gruppierer einen Mechanismus des Arbeitsgedächtnisses nutzen, um den ersten Gedächtnisabruf so lange aktiv zu halten, bis auch die zweite Reaktion abgerufen wurde (Nino & Rickard, 2003). Dies ermöglicht dann eine Verknüpfung der beiden Reaktionen (engl. *chunking*), was wiederum dafür sorgt, dass die verknüpften Reaktionen in einem Schritt gemeinsam durch den Engpass zur Reaktionsstufe gelangen. Somit ist es den Gruppierern möglich, beide Reaktionen in synchronisierter Form mit relativ kurzen IRIs auszuführen. Dieser Prozess wird als gelernter Parallelismus bezeichnet.

Eine Annahme ist, dass der gelernte Parallelismus nicht allgemein für die gesamte Aufgabe, sondern stimulusspezifisch ist. Dies bedeutet, dass sich der Parallelismus nur für Stimuli zeigt, für die das Chunking während der DA-Übung stattgefunden hat. Daraus folgt, dass für neue Stimuli ohne DA-Übung kein Parallelismus gezeigt wird und man bei ungeübten

Stimulus-Reaktionsfolgen sequenzielle Reaktionsmuster erhält. Diese Hypothese der Stimulusspezifität des set-cue bottleneck Modells konnte durch die Studie von Strobach et al. (2014) unterstützt werden. In der ersten Transfertriade gibt es für die Stimuli, die nicht in DA geübt wurden, sequenzielle Verarbeitungsmuster, während für die Stimuli mit DA-Übung weiterhin Parallelismus gezeigt wurde. Diese Ergebnisse unterstützen die Annahme, dass der Verknüpfungsprozess des Parallelismus (d.h. das Chunking) stimulusspezifisch ist.

EIGENE EMPIRISCHE ARBEIT ZU DUALEM GEDÄCHTNISABRUF NACH ÜBUNG

Um die Annahmen des set-cue bottleneck Modells des dualen Gedächtnisabrufes weiter zu untersuchen, war es ein übergeordnetes Ziel dieser Dissertation, die Annahmen des Modells und eine Generalisierung der Resultate von Nino und Rickard (2003) und Strobach et al. (2014) näher zu prüfen. Dabei fokussieren sich die drei Studien in dieser Dissertation auf drei spezifische Faktoren: Aufgabenspezifische Faktoren (Studie 1), explizite Instruktionen (Studie 2) und individuelle Faktoren (Studie 3). Studie 1 beschäftigte sich mit der Frage, ob die bisherigen Ergebnisse zu einem neuen Abrufkontext mit automatisierten Stimulus-Reaktionskombinationen, mehr Übung und in einer anderen Sprache generalisiert werden können und ob die Annahmen des set-cue bottleneck Modells in diesem Kontext weiterhin zutreffen. Studie 2 konzentrierte sich auf die Frage, ob die zwei verschiedenen Reaktionsmuster (Gruppierer vs. Nicht-Gruppierer) durch explizite Instruktionen beeinflussbar sind oder ob diese zwei Muster durch fundamentale individuelle Unterschiede entstehen. Zuletzt beschäftigte sich Studie 3 mit der Frage, ob die Resultate, und die Annahmen des set-cue bottleneck Modells über die Verarbeitungsarchitektur, der bisherigen Studien mit jüngeren Erwachsenen (Nino & Rickard, 2003; Strobach et al., 2014) auf ältere Erwachsene generalisierbar sind.

Studie 1: Der Einfluss von Aufgabenspezifischen Faktoren

Um die Resultate von Strobach et al. (2014) sowie die von Nino und Rickard (2003) zu generalisieren und in einem neuen Aufgabenkontext zu testen, wurden in Studie 1 drei Experimente durchgeführt, die eine neue Stimulus-Reaktionsaufgabe beinhalteten. Während sich die bisherigen Stimulus-Reaktionsmuster auf zwei komplett neu erworbene, episodische Gedächtnisabrufaufgaben konzentriert haben, wurde nun eine neue Aufgabenzusammensetzung mit vornehmlich semantischem Gedächtnisabruf genutzt. Wenn die Mechanismen gedächtnis- und aufgabenübergreifend sind, würden auch bei der Kombination aus einer semantischen und einer episodischen Gedächtnisaufgabe analoge Resultate zu Strobach et al. demonstriert werden. Wenn die Mechanismen jedoch aufgabenspezifisch sind, würden keine analogen Resultate mit semantischem Gedächtnisabruf erzielt werden können.

Die neue Aufgabenzusammensetzung enthielt eine verbale Antonymaufgabe. In dieser Aufgabe mussten die Teilnehmer jeweils das Antonym eines präsentierten Stimuluswortes als verbale Reaktion geben (z.B.: Tag → „Nacht“, Schlecht → „Gut“, Hass → „Liebe“, etc.); insgesamt gab es 14 Antonympaare. Diese neue Aufgabe wurde als automatisierte, semantische Gedächtnisaufgabe klassifiziert, da sie Assoziationen aus dekontextualisiertem Wissen beinhaltet, welches in der Lebenszeit außerhalb des Labors erworben wurde (Loureiro & Lefebvre, 2016). Für die episodische Tastendruckaufgabe wurden die Antonym-Stimuli wie in den vorherigen Experimenten mit einem rechten und einem linken Tastendruck assoziiert (z.B.: Tag → rechts, Schlecht → links, Hass → links, etc.).

In Experiment 1 wurden nur sieben Stimuluswörter während 15 Triaden der dualen Gedächtnisabrufaufgabe präsentiert (geübte Stimuli) und in den Transfertriaden die restlichen sieben Stimuli (ungeübte Stimuli). In Experiment 2 wurden in der Transferphase sowohl die geübten als auch die ungeübten Stimuli präsentiert. Die Ergebnisse in beiden Experimenten zeigten, dass nach Übung die beobachteten Reaktionszeiten unter die modellierten

Reaktionszeiten der ES-Vorhersage fielen. Die Teilnehmer zeigten also die gleichen Muster von Parallelismus, die schon bei Nino und Rickard (2003) und bei Strobach et al. (2014) beobachtet wurden. Ein weiteres repliziertes Ergebnis war, dass auch in diesen Experimenten kein Parallelismus und damit keine synchronisierten Verarbeitungsmuster für die ungeübten Stimuli in der Transferphase gefunden wurden. Dies entspricht der Annahme des set-cue bottleneck Modells, dass dualer Gedächtnisabruf durch eine Kapazitätslimitation auf der Abrufstufe beeinflusst wird und Parallelismus nur nach Übung und durch chunking möglich ist. Um den Einfluss von Übungseffekten näher zu untersuchen, wurde die Anzahl an Wiederholungen in Experiment 3 von 15 auf 40 Übungstriaden erhöht. Auch in diesem Experiment waren die Resultate analog zu vorherigen Studien mit zwei episodischen Gedächtnisabrufen (z.B. Strobach et al., 2014). Zusammen genommen zeigten diese drei Experimente, dass die vorherigen Ergebnisse von Nino und Rickard sowie Strobach et al. auf eine neue Form des Gedächtnisabrufes erweitert werden konnten. Dies unterstützt die Idee, dass der Abruf-Engpass in dualem Gedächtnisabruf einen Mechanismus darstellt, der Gedächtnisdomänen übergreifend ist. Des Weiteren unterstützen die Resultate die Annahme des stimulusspezifischen chunking-Prozesses, der die synchronisierte Ausführung von zwei Reaktionen ermöglicht. Während in den vorherigen Studien die Anzahl an Gruppierern und Nicht-Gruppierern ausgeglichen war, so zeigten sich innerhalb der Experimente in Studie 1 ein erhöhtes Vorkommen von Gruppierern. Dieses Ergebnis zeigt, dass aufgabenspezifische Faktoren wie extensive Übung und die neue Stimulus-Reaktions Kombination für ein erhöhtes Vorkommen von gelerntem Parallelismus verantwortlich sein können. Außerdem konnten die vorherigen Ergebnisse sowohl mit einer englischen Stichprobe geprüft (Experiment 1) und in deutscher Sprache weiter generalisiert werden (Experiment 2 und 3).

Studie 2: Der Einfluss spezifischer Strategieinstruktionen

Studie 2 fokussierte sich auf die Frage welche strategischen Faktoren das Vorkommen von sequentiellem und parallelem Abruf ermöglichen können. Aus diesem Grund wurde in Studie 2 geprüft, ob die zwei verschiedenen Reaktionsmuster (Gruppierer vs. Nicht-Gruppierer) durch explizite Instruktionen beeinflussbar sind. Eine zugrundeliegende Frage zu diesem Aspekt zielt auf die Ursache für die individuellen Unterschiede in den Verarbeitungsmodi und damit den Reaktionszeitmustern zwischen Gruppierern und Nicht-Gruppierern ab (Strobach et al., 2014). Generell könnten die Unterschiede zwischen den beiden Gruppen entweder das Resultat einer strategischen Entscheidung (Jansen, van Egmond, & de Ridder, 2016; Sanbonmatsu, Strayer, Medeiros-Ward, & Watson, 2013) oder individueller Unterschiede aufgrund kognitiver Charakteristiken sein (Süß, Oberauer, Witmann, Wilhelm, & Schulze, 2002). Sollte es sich um eine strategische Entscheidung handeln, könnten die Reaktionszeitmuster durch gezielte Manipulation der Instruktionen verändert werden. Um diese Annahme zu testen und die strategische Basis von Parallelismus zu prüfen, wurden in Experiment 1 Instruktions-manipulationen für die Bearbeitung der DA in drei verschiedenen Teilnehmergruppen angewendet: Neutrale Instruktion, Gruppierungs-Instruktion, und Nicht-Gruppierungs-Instruktion. In der neutralen Instruktionsgruppe wurde die Instruktion aus den vorherigen Studien genutzt: Diese Teilnehmer wurden lediglich instruiert, so schnell und fehlerfrei wie möglich zu reagieren. In der Gruppierungs-Instruktionsgruppe wurden die Teilnehmer angeleitet, auf den Abruf von beiden Reaktionen zu warten und sie dann gleichzeitig (d.h. synchronisiert) auszuführen. Dahingegen sollten Teilnehmer in der Nicht-Gruppierungs-Instruktionsgruppe die erste Reaktion geben, sobald sie abgerufen wurde. Erst danach sollte die zweite Reaktion gegeben werden. In der Transferphase erhielten alle Teilnehmer die neutrale Instruktion. Analog zu Nino und Rickard (2003) wurde bei diesem Experiment ein Set von zehn Stimulus-Reaktionskombinationen und zwei episodischen Gedächtnisaufgaben präsentiert.

Die Ergebnisse von Experiment 1 zeigten, dass die Teilnehmer fähig waren die jeweilige Instruktion umzusetzen. Bei neutraler Instruktion gab es analog zu den vorherigen Studien (Nino & Rickard, 2003; Strobach et al., 2014) Teilnehmer, die sowohl sequenziellen als auch synchronisierten Abruf zeigten. In der Gruppierungs-Instruktionsgruppe zeigten alle Teilnehmer sehr kurze IRIs. Des Weiteren zeigte sich die gleiche Form von Parallelismus, die in vorherigen Studien von den Gruppierern gezeigt wurde. Im Kontrast dazu zeigten die Teilnehmer der Nicht-Gruppierungs-Instruktionsgruppe relativ lange IRIs und stark sequenzielle Reaktionszeitmuster, die der ES-Vorhersage entsprachen. In Experiment 1 zeigte sich in der Transferphase, dass manche der Probanden die Strategie wechselten. Dieses Ergebnis spricht für die Existenz von individuellen Strategiepräferenzen, welche bereits in anderen Studien gefunden wurden (Brüning & Manzey, 2018; Fischer & Plessow, 2015; Reissland & Manzey, 2016).

Als Erweiterung von Experiment 1, beinhaltete Experiment 2 drei zusätzliche Modifikationen, um die Annahme des stimulusspezifischen chunkings tiefergehend zu prüfen. So wurden im Verlauf der Übung nur sieben Stimuli (i.e., geübte Stimuli) der vorab 14 erlenernten Stimuli präsentiert und erst in der Transferphase die weiteren sieben (i.e., ungeübten) Stimuli präsentiert. Während der Übung gab es nur noch eine Gruppierungs- und eine Nicht-Gruppierungs-Instruktionsgruppe und die Instruktionen wurden nach der Übung in der Transferphase nicht verändert.

Wie bereits in Experiment 1, konnten die Instruktionen während der Übungsphase auch in Experiment 2 umgesetzt werden. Die Transferphase in Experiment 2 zeigte darüber hinaus, dass die Probanden in der Gruppierungs-Instruktionsgruppe während der ersten Transfertriade nicht fähig waren, für die ungeübten Stimuli synchronisierte Reaktionen zu zeigen, während sie für die geübten Stimuli weiterhin der Instruktion folgen konnten. Die Ergebnisse beider Experimente zum (instruierten) Parallelismus sind generell konsistent mit den Annahmen des set-cue bottleneck Modells und seinem Chunkingsprozess. Zusätzlich zeigen die Ergebnisse von Studie 2, dass die Strategien des dualen Gedächtnisabrufes flexibel sind und es keine individuellen fundamentalen kognitiven Unterschiede zwischen den Personen gibt, die einem sequenziellem oder einem synchronisiertem Abrufmuster folgen.

Studie 3: Der Einfluss des individuellen Faktors Alter

Studie 3 fokussierte sich auf die Möglichkeit der Generalisierung der bisherigen Ergebnisse zu einer neuen Altersgruppe. Die bisherigen Studien wurden mit Stichproben von jungen Erwachsenen im Alter von 18 bis 30 Jahren durchgeführt. Dadurch stellte sich die Frage, ob auch ältere Erwachsene die gleiche Verarbeitungsarchitektur aufweisen und ob die Annahmen des set-cue bottleneck Modells auch für Erwachsene im Alter von 55 bis 70 Jahren gültig sind. Die Ergebnislage in vorherigen DA-Studien präsentiert ein gemischtes Bild: Während einerseits Ergebnisse gefunden wurden, die zeigten, dass ältere Erwachsene ein Defizit in der DA-Verarbeitung aufweisen (Riby, Perfect, & Stollery, 2004), konnten andere Ergebnisse dies nicht bestätigen (Tun & Wingfield, 1993). Ein übergreifendes Ergebnis aus der Literatur ist jedoch, dass ältere Erwachsene im Vergleich zu jüngeren Erwachsenen generell längere Reaktionszeiten in DA zeigen (Vaportzis, Georgiou-Karistianis, & Stout, 2013). Durch Übung der DA-Aufgaben scheinen ältere Erwachsene jedoch in der Lage zu sein die Leistung bei DA zu verbessern und die Reaktionszeiten zu verringern (Strobach, Frensch, Müller, & Schubert, 2012). Dabei bleibt es jedoch weiterhin eine offene Frage, ob ältere Leute im gleichen Maß wie jüngere Leute von Übung profitieren.

Studie 3 umfasste zwei Experimente mit jeweils zwei unabhängigen Experimentalgruppen (jüngere Erwachsene vs. ältere Erwachsene) im Alter von jeweils 19 bis 30 und 55 bis 71 Jahren. Experiment 1 hatte zum Ziel die bisherigen Ergebnisse der Studie von Strobach et al. (2014) zu replizieren und zu prüfen, ob die bisherigen Ergebnisse über die Verarbeitungsarchitektur des dualen Gedächtnisabrufes auch für die Gruppe älterer Erwachsener gültig sind. Das Design von Experiment 1 entsprach daher einer Replikation von

Experiment 1 aus Strobach et al. (2014). In Experiment 2 wurde das Design so weit verändert, dass bereits alle 14 Stimulus-Reaktionskombinationen während der EA innerhalb der Triaden präsentiert wurden, um die Exposition und die Übung zu erhöhen, was einen stärkeren Test der Annahmen des set-cue bottleneck Modells ermöglichte.

Die Ergebnisse zeigten generell längere Reaktionszeiten in älteren im Vergleich zu jüngeren Erwachsenen. Allerdings konnten beide Altersgruppen die Reaktionszeiten im Verlauf der Übung deutlich verkürzen. In beiden Experimenten und innerhalb beider Altersgruppen zeigten sich sowohl Gruppierer als auch Nicht-Gruppierer welche jeweils keine qualitativen Unterschiede in der Verarbeitung der DA zwischen den Altersgruppen aufwiesen. Ältere sowie jüngere Erwachsene waren gleichsam fähig, gelernten Parallelismus zu zeigen. Zudem konnte die Annahme der Stimulusspezifizität des Chunkings in der jüngeren Altersgruppe repliziert und für ältere Erwachsene generalisiert werden.

ZUSAMMENFASSUNG

Zusammenfassend lässt sich sagen, dass die kognitive Verarbeitungsarchitektur des dualen Gedächtnisabrufs von einem Stimulus mit Hilfe der Studien in dieser Dissertation näher spezifiziert und geprüft werden konnte. Im Rahmen der drei hier vorgestellten Studien konnten zudem die theoretischen Annahmen des set-cue bottleneck Modells empirisch geprüft und unterstützt werden. Innerhalb aller drei Studien konnte das Vorkommen des gelernten Parallelismus nach Übung im Rahmen von stimulusspezifischem Chunking herausgestellt werden. Dabei wurde zudem das Zusammenspiel von drei Faktoren näher erforscht. Der aufgabenspezifische Faktor „Übung" konnte innerhalb jeder der drei Studien als zentral herausgestellt werden, da die Notwendigkeit von Übung von Stimulus-Reaktionskombinationen in DA-Situationen als essenzieller Faktor für die Entstehung von parallelem Abruf innerhalb aller drei Studien demonstriert werden konnte und somit die Annahme der Stimulusspezifizität im Rahmen des set-cue bottleneck Modells weiter unterstützt werden konnte. Zusätzlich zeigte sich durch die spezielle neue Aufgabenkombination aus semantischen und episodischen Gedächtnisinhalten in Studie 1 die mehrheitliche Entstehung des synchronisierten Abrufs im Vergleich zu den Studien welche nur episodische Gedächtnisinhalte nutzten (Nino & Rickard, 2003; Strobach et al., 2014). Neben den aufgabenspezifischen Faktoren konnten in Studie 2 auch Instruktionen als einflussreich hervorgehoben werden. Diese Studie konnte vor allem zeigen, dass die Probanden in der Lage waren, unterschiedlichen Strategieinstruktionen zu folgen und somit die Hypothese stützen, dass es eher nicht individuelle kognitive Unterschiede sind, welche die Entstehung von sequentiellem und synchronisiertem Abruf beeinflussen. Außerdem konnte Studie 2 weiterhin die Annahmen der Stimulusspezifizität des Chunking Prozesses innerhalb des set-cue bottleneck Modells stützten. Hinsichtlich individueller Faktoren konnte Studie 2 weiterhin Hinweise darauf geben, dass es individuelle Strategiepräferenzen gibt, welche jedoch flexibel durch Instruktionen gesteuert werden können. Die weitere Exploration individueller Faktoren in Studie 3 zeigte, dass Alter zudem nicht als beeinflussender Faktor für die grundlegende Verarbeitungsarchitektur im Rahmen des set-cue bottleneck Modells herausgestellt werden konnte. Trotz generell längeren Reaktionszeiten profitierten ältere Erwachsene von Übung und zeigten die gleichen Verarbeitungsmuster wie jüngere Erwachsene. Abschließend lässt sich zusammenfassen, dass die Annahmen des set-cue bottleneck Modells des dualen Gedächtnisabrufs von einem Stimulus innerhalb der Studien dieser Dissertation weiter unterstützt werden konnten und die Ergebnisse der ursprünglichen Studien von Nino und Rickard (2003) sowie von Strobach et al. (2014) sowohl repliziert als auch weiter generalisiert werden konnten.

INTRODUCTION

THE IMPORTANCE OF DUAL-TASK RESEARCH

Due to the increasing demands on the human processing system because of technological advances and heightened requirements in the workplace, humans are required to complete more and more tasks in a shorter amount of time. Sometimes, some tasks even need to be performed at the same time. Looking into the daily life of many people, a practical example out of the workplace could be an important phone conference with project partners which require the simultaneous search for specific numbers in an excel sheet or writing a detailed protocol during the conference call. Therefore, there is an increasing demand to investigate the cognitive mechanisms that are required when humans engage in tasks that mandate complex forms of information processing. One of the related research areas that has gained increasing attention over the last decades is the research on dual-tasking. Dual-tasking refers to the engagement in two distinct tasks at the same time and is colloquially often referred to as multitasking.

In the scope of the present research, it is important to distinguish between daily life situations that involve the execution of two tasks at the same time, as in the example above, and dual-tasking in a cognitive research laboratory context. While there is a small body of research that focusses on applied, daily life activities, involving dual-tasking (such as Hillel et al., 2019; Salvucci, 2005; Schaefer, Koch, & Philipp, 2014) the scope of the work discussed in this dissertation is on the well-controlled investigation of performance of two distinct tasks in the laboratory. It is important to establish this difference, as the present work is using experimental lab-situations to investigate the exact mechanisms that influence the cognitive processing architecture in a dual-tasking context.

Since several years, researchers are debating about the processing architecture that builds the foundation of dual-tasking. When humans have to perform two tasks at the same time, we are able to observe performance decrements that are defined as dual-tasks costs. These costs generally refer to the slowing of responses or a larger amount of errors that are not observed when the two tasks are performed on their own in an isolated, single-task, context (Kahneman, 1973; Pashler, 1994; Welford, 1952). Dual-task costs and other dual-task performance findings have been investigated across different frameworks and models. One of the most prominent frameworks involves choice reaction time (RT) tasks, such as the Psychological Refractory Period (PRP) paradigm (Pashler, 1994; Welford, 1952). In this paradigm, two stimuli (e.g., S1 and S2) are associated with two different responses (e.g., R1 and R2). The stimuli are presented with varying intervals and subjects are required to respond as fast as possible to both stimuli with a priority on S1. The main finding, which has been defined as the PRP effect, is that shortening the interval between the presentation of S1 and S2 is causing a prolongation of the RT on R2 (Meyer & Kieras, 1997; Pashler, 1994). One of the central and widely discussed assumptions that came along with the PRP effect is the assumption of a central bottleneck (Pashler, 1994, 1998; Pashler & Johnston, 1989). According to the central bottleneck, humans have to complete the central processing of S1 before they are able to engage in the processing of S2. While this view of a capacity constraint has found a lot of support, there also has been criticism associated with the assumption of the central bottleneck model (see Navon & Miller, 2002 for an overview). One of the main arguments against this model is that it only allows sequential, or serial, processing and does not include the possibility for parallel, or simultaneous, processing of two stimuli (Meyer & Kieras, 1997; Miller, Ulrich, & Rolke, 2009; Tombu & Jolicœur, 2003). However, the assumption that parallel processing is indeed possible has been made by several authors which have used modified versions of the PRP paradigm (Fischer, Miller, & Schubert, 2007; Hommel, 1998; Janczyck, Pfister, Hommel, & Kunde, 2014; Ko & Miller, 2014; Logan & Schulkind, 2000; Miller & Alderton, 2006; Schumacher at al., 2001; Tombu & Jolicoeur, 2003).

Practice and Dual-Memory Retrieval

An important factor which has been in the focus of dual-tasking research and the PRP effect is that dual-task practice can account for strong reductions of dual-task costs (e.g., Hazeltine et al., 2002; Liepelt et al., 2011; Schumacher at al., 2001; Strobach et al., 2012a; Strobach, Liepelt, Schubert, & Kiesel, 2012; Tombu & Jolicoeur, 2004) and even almost eliminate the PRP effect (Van Selst, Ruthruff, & Johnston, 1999). Though, while this issue has been discussed in depth in the context of the PRP paradigm and the central bottleneck model, there is a lack of research on the cognitive processing architecture and practice effects in other areas of dual-tasking. One of these underdeveloped areas is dual-memory retrieval, which constitutes the main focus of the present work. Dual-memory retrieval, as discussed in the context of this dissertation, can be defined as a specific subcomponent of dual-tasking and engages two memory retrievals from long-term memory.

In particular, the present work is focused on the retrieval of two distinct and resource independent responses from a single cue (i.e., one specific cue is associated with two different responses). Only a very scarce amount of studies has previously been conducted on this type of task and the cognitive processing architecture that is associated with the performance and practice of this task (Nino & Rickard, 2003; Rickard & Pashler, 2005; Strobach et al., 2014). According to this, the cognitive models in this area of research are presently still rather unexplored. However, it is important to investigate the mechanisms that are associated with dual-memory retrieval from long-term memory since, as mentioned above, this task design is able to investigate the characteristics of the human cognitive system that are at play under substantial task demands (Meyer & Kieras, 1997; Townsend & Wenger, 2004). The design further presents an advantage in comparison to other dual-tasking designs since using the retrieval of two responses from one single cue eradicates the process of selection and discrimination between two different cues. This additionally lessens the burden on divided attention and gives the advantage of lower task interference, which might establish a driving factor in the emergence of dual-task costs (Fagot & Pashler, 1992). Insights into this specific processing architecture of dual-memory retrieval can aid the understanding of the human mind which is increasingly confronted with challenging demands related to fast technological advances and rapid changes in the workplace (Otto, Wahl, Lefort, & Frei, 2012; Rothbarth & Posner, 2015). To implement new models on efficient strategies to cope with rising multitasking demands, we need to understand the basic processing architecture that takes place when we try to retrieve the information that is related to the performance of two tasks at once.

Dual-memory retrieval from a single-cue: Task and procedure

As established in the previous section, the present research resolves around dual-memory retrieval from a single cue. In this section, I am going to explain the specific task and procedure which has been used throughout my empirical studies. In all of my studies, I have used and adapted the procedure initially described by Nino and Rickard (2003) and later modified by Strobach et al. (2014). The previous studies as well as the ones discussed in this work involved two- to three-session computerized experiments. Within each study and for each participant, all of these sessions were conducted in the course of seven days. Before I will discuss the exact procedure, I am going to explain the task set-up.

In general, the task involved the presentation of a specific cue word which has been associated with two different responses. The cue words were color words like *red*, *green*, *blue*, et cetera. Each of these cue words was associated with a specific vocal response and a keypress response. These cue-response associations marked two different retrieval tasks: the vocal task and the keypress task. The vocal task involved a verbal response by speaking a digit into a microphone. This means that after, for example, the cue word *red* was presented, subjects had to speak the digit "*five*" into the microphone. Each specific cue word only had one specific vocal response (i.e., digit association) linked to it. In the keypress task, each color cue word was associated with a direction, either left or right. The direction needed to be indicated by a lever-press on a keypress pad. Taking the previous example of the cue-word *red*: When *red* was presented on the screen, subjects had to press the *"left"* key on the keypress pad. It has to be noted that all cue words were presented in black font. A visualization of the cue-response associations can be found in Figure 1A.

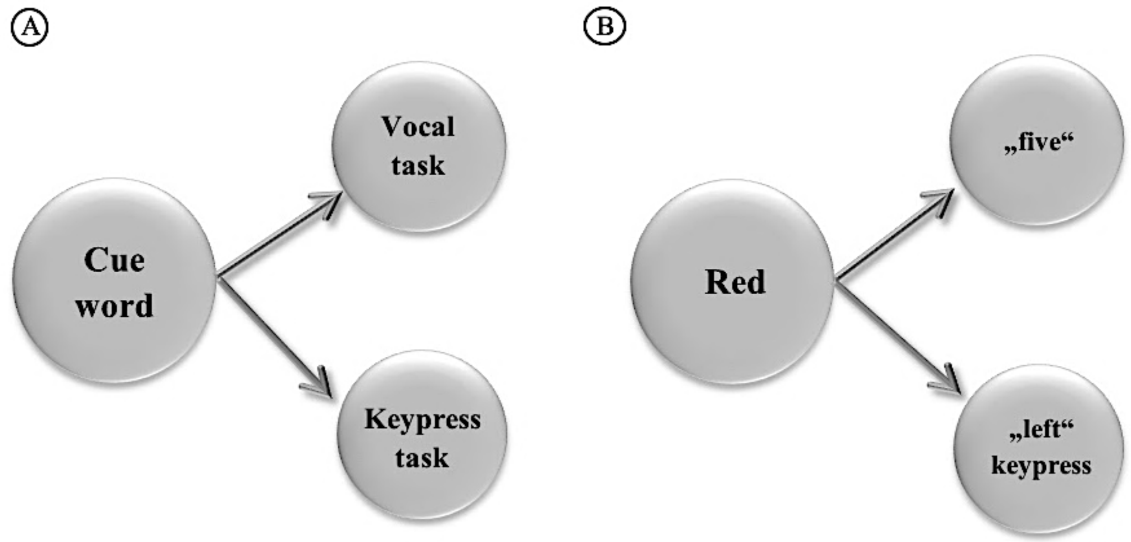

Figure 1. Illustration of cue-response associations in the dual-memory retrieval task from a single cue. Panel A illustrates the task construction: One specific cue word is associated with one specific vocal response and one specific keypress response. A detailed example is depicted in panel B: when the cue word "red" is presented on the computer screen, the vocal task response is to speak the word "five" into the microphone and the keypress response is to press the left key on the keypress pad.

The core procedure across all previous (Nino & Rickard, 2003; Rickard & Pashler, 2005; Strobach et al., 2014) and my present experiments was fairly similar[1]. As stated above, each experiment involved three experimental sessions. Each of the sessions had a duration of approximately one hour. In general, Session 1 comprised the learning period and Session 2 and 3 comprised the experimental practice periods. Session 1 always started with an introduction to both retrieval tasks. Each task was learned individually, and subjects were only introduced to the next task after they had studied and practiced each cue and response association of the first

[1] In my following description of the procedure, I am going to generally focus on the procedure of Strobach et al. (2014) which involved an additional transfer phase that was not present in the initial study of Nino and Rickard (2003).

task. Each single cue was defined as a *trial*. The presentation of all of the cues (i.e., all trials) was defined as a *block*. All trials were randomly presented in each block. At the end of Session 1, the single vocal as well as the single keypress task were both practiced in alternating order for five blocks for each task.

Session 2 started with a repetition of the practice from Session 1 (i.e., five blocks per task in alternating order). After this phase, the *single-dual practice phase* started which marked the beginning of the experimental phase. This phase involved the practice of triads (i.e., the experiments by Strobach et al. (2014) used 20 practice triads). As depicted in Figure 2, a triad refers to the presentation of three blocks: one block of the single keypress task, one block of the single vocal task and one block of a new dual-retrieval task. In the dual-retrieval blocks, subjects were instructed to give both responses as fast and as accurately as possible. In Strobach et al. (2014) this single-dual practice phase involved the presentation of seven of the fourteen previously learned cues. This means that this phase incorporated seven trials per block. Ten triads were presented in Session 2 and the remaining ten were presented in Session 3.

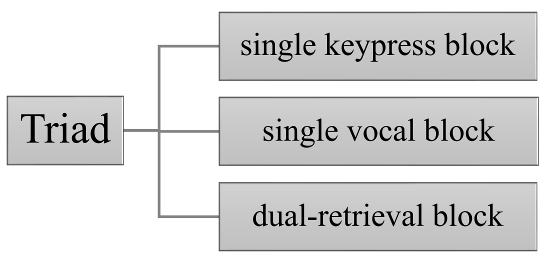

Figure 2. Visual depiction of the three components of a triad. In each of the three blocks, all practice trials from one task are completed before the start of a new block.

Session 3 ended with the *single-dual transfer phase*. This phase incorporated five additional triads. However, these triads only comprised of the remaining seven cues that were not presented during the previous practice. In the course of the past and my present experiments, practiced cues (i.e., practiced in single-dual triads during practice) are referred to as *old cues* and unpracticed cues (i.e., introduced to single-dual triads during transfer) are referred to as *new cues*. Using these new and unpracticed cues at the end of practice enabled the assessment of transfer effects. I am going to describe the assessment methods and rationale of these effects in detail in the next section which is going to focus on the assessment of the cognitive processing architecture with the use of data pattern analyses.

ASSESSMENT OF THE COGNITIVE PROCESSING ARCHITECTURE

The following subsections are focusing on the empirical, theoretical, and methodological base of the present work. The main assessments to investigate the cognitive processing architecture of dual-memory retrieval from a single cue involve the analyses of the RT patterns that emerge during the practice and transfer phases.

INTER RESPONSE INTERVALS: GROUPER VERSUS NONGROUPER SUBJECTS

One of the first steps in the analyses of response patterns was the inspection of individual RTs across the practice phase. This inspection involved the examination of the inter-response interval (IRI) on dual-retrieval trials. An IRI refers to the difference between RT1 (the first response, i.e., the latency between the stimulus presentation and the first executed response) and RT2 (the second response; i.e., the latency between the stimulus presentation and the second executed response). This IRI was computed for each individual subject across practice and sorted from shortest to longest.

When sorting the IRIs, in Strobach et al. (2014) as well as in Nino and Rickard (2003), a gap between the responses was seen at around 300ms. This gap indicated the presence of two different types of response styles. Apparently, one group was marked by short IRIs whereas the other group was marked by longer IRIs. This shows that one type of subjects seems to give both responses in very short succession whereas the other group takes a longer time between the first and the second response. The latter group was classified as *nongrouper* subjects because their long IRIs seemed to indicate a sequential responding pattern. In contrast to that, the other group seemed to synchronize, or group, their responses which was marked by distinctly shorter IRIs.

Therefore, these individuals were classified as *grouper* subjects (Nino & Rickard, 2003).

The efficient sequential (ES) retrieval model

In order to analyze and categorize these two previously stated response patterns shown by subjects during practice, prior experiments have used the quantitative predictions of the *efficient sequential (ES) retrieval model* (Nino & Rickard, 2003; Rickard & Pashler, 2005; Strobach et al., 2014). The ES model is used to predict RTs that would be exhibited if subjects would present sequential retrieval processing. Comparing the averaged RTs of the nongrouper subjects to the ES prediction revealed that, while the initial RTs were above the ES prediction at the onset of practice, they converged on almost the same values as the ES prediction. Subsequently, it was concluded that this subgroup indicated sequential retrieval throughout practice (Nino & Rickard, 2003).

The ES model features three main assumptions. First of all, the perceptual, retrieval, and motor stages of processing are independent and sequential. Second, there is a bottleneck which exclusively exists at the memory retrieval stage of processing. This bottleneck allows only the processing of one task at a time at the retrieval stage. However, the perceptual and motor stages can still process in parallel to the retrieval stage. And third, the coordination of all three processing stages (i.e., perceptual, retrieval and motor) is maximally efficient during dual-retrieval. This means that there are no, or only very little, interruptions in task coordination or task control.

The ES model uses single-task RTs as predictors for the sequential-dual retrieval. In the mathematical model, the equation sums up the latency distributions of the perceptual, retrieval and motor stage for a given cue and the given response. For sequential retrieval, the first response (RT1; i.e., latency between the stimulus presentation and the first executed response) is assumed to reflect the same stage sequence as a single-retrieval trial. The second response (RT2; i.e., latency between the stimulus presentation and the second executed response) includes the latency components of all three stages and additionally adds the motor stage of the second-executed task (i.e., either vocal or keypress). Since the quantitative model for RT2 incorporates additional latencies for the perception and motor stage of the second response, a correction parameter is used to compensate for the extra terms. This is important since perception stages would otherwise be counted twice. Additionally, the motor stage, which could occur in parallel with the retrieval stage of the second completed task, would further add to the model. Therefore, the correction parameter is needed in order to avoid falsely increased predicted RTs in the ES model that are larger than the actually observed RTs. These empirically motivated correction factors refer to –200ms, in the case of the execution of the vocal response first, and to –250ms, when the keypress response is executed first. According to Nino and Rickard (2003) these factors refer to the excess amount of time that would be added to the model by the time needed for cue perception and motor output.

The ES model has been defined as a lower bound RT estimate for sequential processing at the (assumed) bottleneck stage of retrieval. If the observed RT patterns are above or equal to the patterns predicted by the ES model, it can be concluded that sequential retrieval has been observed which would be in accordance with the hypotheses of the model. In contrast, if the observed data would violate the ES prediction by falling significantly below, it can be concluded that the response patterns reflect a different kind of processing which does not fit to the assumption of a sequential retrieval stage (Nino & Rickard, 2003; Rickard & Pashler, 2005; Strobach et al., 2014). While this model can be classified as a model of best fit for the nongrouper subjects, who exhibited sequential retrieval, a different picture emerged for the RTs of grouper subjects: While their RT results were also above the values predicted by the ES prediction at the onset of practice, which was indicative for sequential retrieval, their RT2 values fell significantly below the ES prediction throughout practice. This indicated a violation of the sequential model for this subgroup of subjects and implied a form of *learned retrieval parallelism* (Nino & Rickard, 2003).

THE SET-CUE BOTTLENECK MODEL

Since I previously discussed the presence of a bottleneck in the human processing architecture in dual-tasking processes, it remained an open question how subjects should be able to engage in the phenomenon of learned retrieval parallelism. A number of authors suggested that, after practice, subjects would make a strategic switch from sequential to parallel retrieval which should not be associated with a structural constraint (Meyer & Kieras, 1997; Oberauer & Bialkova, 2011; Oberauer & Kliegl, 2004). Alternatively, according to Nino and Rickard (2003), it could be argued that grouper subjects were able to simultaneously activate both responses in working memory which allowed them to chunk both responses and to retrieve them in one pass through a central processing bottleneck (Fagot & Pashler, 1992).

This process can be described by the *set-cue bottleneck model* (Figure 4) of dual-memory retrieval (Nino & Rickard, 2003). The set-cue bottleneck model incorporates the assumption of three independent, sequential and additive processing stages: (1) perceptual stage, (2) central retrieval stage, and (3) motor processing stage. The perceptual stage incorporates the activation stream that occurs right from the moment of cue-presentation up to activation of the retrieval stage at the input level. The central retrieval stage reaches from the moment of activation (i.e., when the cue perception process activates the threshold at the input level) to the activation of the response level. The motor processing stage comprises the activation stream from the response level to the finalized execution of the response.

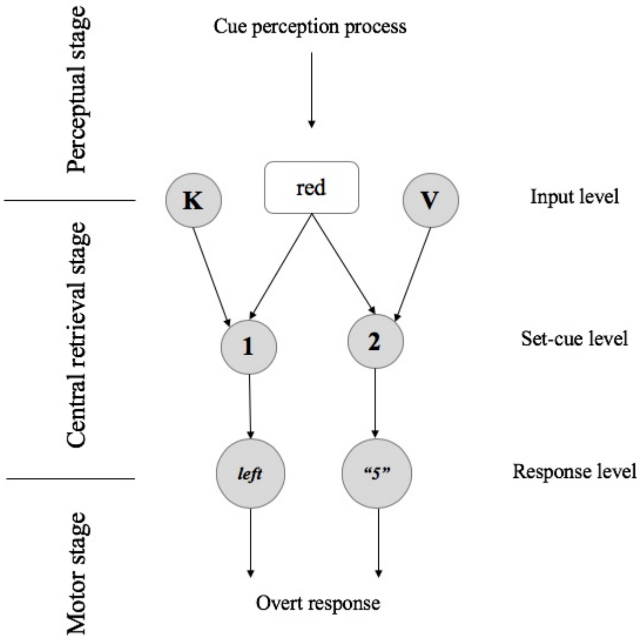

Figure 4. Graphical illustration of the basic architecture of the set-cue bottleneck model of dual memory retrieval (adapted from Orscheschek, Strobach, Schubert, & Rickard, 2019). The model comprises the perceptual, retrieval and motor stages of processing. The nodes at the input level symbolize the cue and the tasks sets (i.e., *K* refers to the task set node of the keypress task; *V* refers to the task set node of the vocal task). At the set-cue level, the nodes represent the combination of the cue and the task set. These task sets nodes are associated with the nodes at the response level.

In the set-cue bottleneck model, associations can only be formed between activated nodes at neighboring levels of the model. As we can see in Figure 4, the nodes at the input level resemble the presented cue and also the task sets. The task sets refer to the associated responses: The goal to complete one of the available responses associated with the cue. The task set node *K* refers to the keypress task and to perform a correct keypress response upon cue presentation. The same holds for the task set node *V*, which refers to the vocal task and the correct execution of a vocal response after cue presentation. At the set-cue level, we have two nodes as well. Each of these nodes resembles the combination of the cue and the associated task set (i.e., either keypress or vocal). The task set nodes at the set-cue level, also have an association with the nodes at the response level.

One of the main assumptions of the model is that activation can stream in parallel from cue-perception, over the input level, to the set-cue level. From the set-cue level, the activation can further flow in parallel over the response level to the motor stage. However, there is a capacity constraint (i.e., the bottleneck) at the set-cue level. At this level, Nino and Rickard (2003) assumed a winner-take-all competition. This means that one of the set-cue nodes, which will be activated first, is selected and starts the process of activation flow to the response level. The whole retrieval stage needs to be completed for the winning response, before the second retrieval can take place. This means that the second retrieval cannot start until the threshold activation on the response level has been reached. However, this does not mean that the motor response for the first retrieved task needs to be performed immediately after retrieval is completed. Instead, the model only requires completion of the retrieval stage, not immediate execution of the response.

While sequential responders (i.e., nongrouper subjects) seem to perform the first response as soon as the retrieval is finished and then start with the retrieval and response process of the second task, synchronized responders (i.e., grouper subjects) do not seem to engage in this procedure. According to the set-cue bottleneck model, grouper subjects should be able to engage in a chunking process that occurs over practice (Figure 5). This means that initial retrievals are following a sequential response pattern, governed by the bottleneck at the central retrieval stage. Throughout practice, grouper subjects synchronize their response execution, by actively holding the first retrieval in working memory while the retrieval of the second response is taking place. In terms of the model, while each response is only associated with its own set-cue node at the beginning, both responses develop an association with the second set cue node which was initially only associated with the second response. This joint activation develops through the process of holding the first response active in working memory while the retrieval of the second response is taking place. While the second response is retrieved a total of three nodes are activated at the same time. These are the nodes for the first retrieved response, the node for the second retrieved response and the set-cue node associated with the second retrieval. This results in the association of the second set-cue node with both responses. When this chain of associations is established, the second set-cue node will further on be the leader in the winner-take-all competition. This process then allows parallel retrieval from one set-cue node.

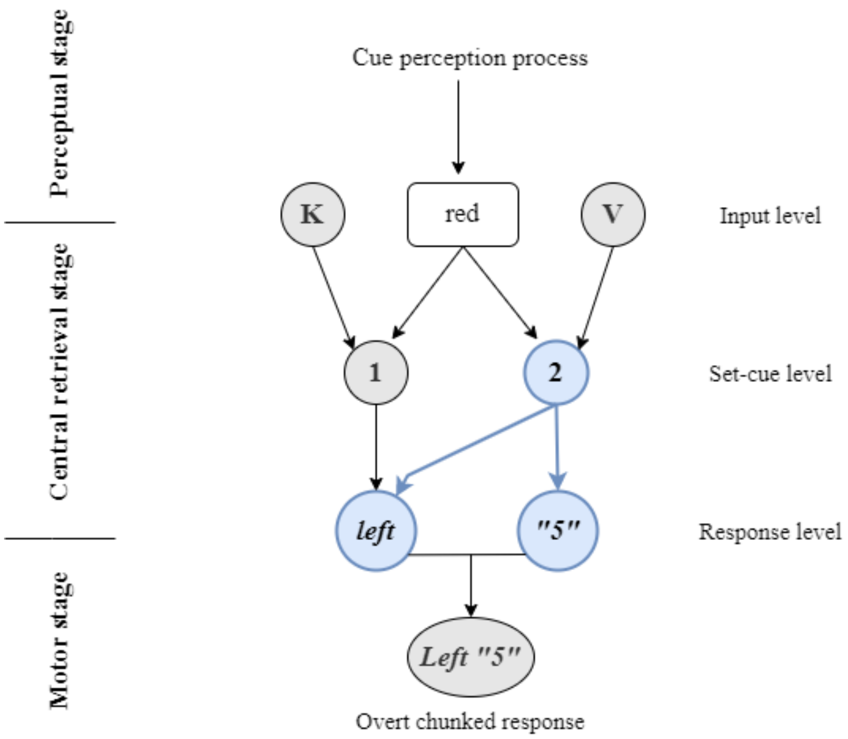

Figure 5. Graphical illustration of the chunking process in the framework of the set-cue bottleneck model of dual- memory retrieval (adapted from Orscheschek et al., 2019). The extended illustration of Figure 4 highlights the joint activation of the three relevant nodes, the set-cue node and both responses (i.e., the blue nodes), which forms the central process to allow for parallel retrieval from one set-cue node. It further illustrates the synchronized motor response at the motor stage.

The presumed chunking mechanism, which requires practice, allows the occurrence of parallelism without violating the core assumption of the model that the central retrieval stage only permits processing of one set-cue node at a time. Moreover, this chunking process is assumed to be *cue-specific*. Meaning that, in the set-cue bottleneck model, response chunking and learned retrieval parallelism are not associated with task-level learning and are therefore not assumed to be task-specific. Instead, the chunking process is occurring independently for each single cue (Nino & Rickard, 2003).

Testing the Assumptions of the Set-Cue Bottleneck Model

It could be argued that the occurrence of learned parallelism would speak against the assumption of a bottleneck stage of retrieval. However, previous studies have been in favor of the assumptions of the set-cue bottleneck model of dual retrieval. In the previous studies by Nino and Rickard (2003) and Strobach et al. (2014) subjects were not able to engage in parallel retrieval from the start of practice. They only started to engage in parallel responding after dual-retrieval practice. This speaks for the assumption that parallelism is indeed a learned process and requires certain mechanisms (i.e., chunking) to occur in order to enable the occurrence of parallelism. Strobach et al. (2014) were able to perform a further test on the assumptions of the set-cue bottleneck model by implanting the previously described transfer phase and by manipulating the amount of cue presentations across practice. Subjects in this study initially learned fourteen cue-response pairings for each task. However, only seven of these cue-response pairings were practiced during the practice phase. In the transfer phase, the remaining seven cues were presented.

If response grouping, and therefore learned parallelism, would be a strategic choice operating at a task level, and not influenced by any capacity constraints (Meyer & Kieras, 1997; Oberauer & Bialkova, 2011; Oberauer & Kliegl, 2004) subjects that exhibited learned parallelism during practice with the practiced (i.e., old) cues, should also be able to perform the same response patterns with unpracticed (i.e., new) cues since they should have strategically chosen to adapt to parallel responding. In contrast, Strobach et al. (2014) found that all subjects exhibited sequential retrieval at the outset of the transfer phase for new cues, whereas the grouper subjects were still performing learned parallelism for the old cues. This finding was supportive of the assumptions of learned parallelism and cue-specific chunking after practice (i.e., these findings were not in favor of the task-level account), and it was further in line with the assumptions of the set-cue bottleneck model.

While the set-cue bottleneck model seems to be a qualified candidate model to account for the cognitive processing architecture of dual memory retrieval from a single cue, the small amount of previous research leaves several open questions: Will the assumptions and predictions of the set-cue bottleneck model be generalizable to different cue-response combinations, different age groups and more practice? What are the underlying mechanisms that influence the differences in response grouping and nongrouping? And, are the differential response styles based on inflexible person-inherent factors or are they based on strategic factors that can be adapted and controlled? These open questions are building the foundation for the central objectives of the present work.

The Present Work: Three Potential Factors of Influence

The present work targets a further examination of the cognitive processing architecture of dual memory retrieval from a single cue. With this work, I am aiming to advance our knowledge on the processing architecture and to test the predictions of the set-cue bottleneck model by expanding the previously designed dual-retrieval task to new cue-response associations, different memory domains, strategy manipulations as well as distinct age groups. While previous research has been able to establish the occurrence of two different response types across dual-memory retrieval practice from a single cue, we still lack information on the factors that impact the emergence of these response types (i.e., response grouping and nongrouping). In particular, I am focusing on the examination of three factors that could play a critical role in the occurrence of the differences in retrieval processing of grouper and nongrouper subjects. These factors are *task specific factors*, *explicit strategy instructions* and *individual factors* (please see Figure 6 for a graphical illustration). Task specific factors refer to elements of the dual-retrieval task that could influence the presence of distinct response patterns. Examples of such factors are practice, changes in task demands such as higher or lower cognitive load or the engagement of new memory domains. Practice has been proven to be an important factor when it comes to dual-task cost reduction (e.g., Göthe, Oberauer, & Kliegl, 2016; Kamienkowski et al., 2011; see Strobach, 2020 for a review) and it was further shown that learned parallelism seems to require at least some amount of practice to be adapted by individuals (Nino & Rickard, 2003; Strobach et al., 2014).

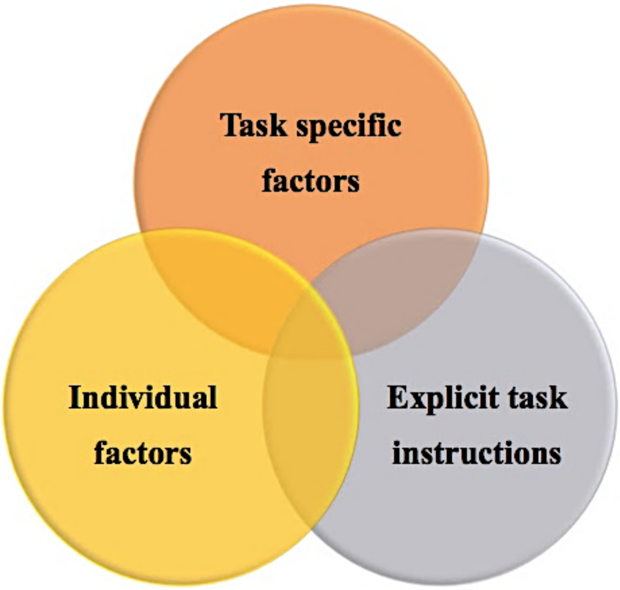

Figure 6. Illustration of the three potential components which can be assumed to play a critical role in the retrieval and response patterns in dual-memory retrieval from a single cue. It is assumed that not only one of these factors, but rather an interplay of all of them accounts for differences and changes across dual-retrieval practice.

However, it is still unknown how extended levels of practice might influence the response patterns in the task developed by Nino and Rickard (2003). Additionally, while the previous research on dual-memory retrieval from a single cue discussed in this work has focused on the retrieval of two novel cue-response associations, response patterns might be different if the cue-response combinations are not novel but already existing and automatized associations. Therefore, Study 1 focused on the question if the previous findings might generalize to a new task context which implemented automatized cue-response associations. Further, practice levels were modified as well to test the impact of extended dual-retrieval practice on retrieval patterns. Additionally, Study 1 also included experiments in English and

German, to generalize previous findings from English-speaking participants to a new language context with a German-speaking population.

After the assessment of specific task factors in Study 1, I focused on the impact of explicit strategy instructions in Study 2. The central demand of this study was to test if the different response patterns might be caused by fundamental individual differences or if they are moderated by strategy preferences. Therefore, I applied strategy manipulations to assess the impact of explicit task instructions. This investigation allowed me to test if response grouping and nongrouping were motivated by fundamental individual differences, such as different functional abilities like disparities in working memory capacity, or if subjects would merely have a strategy preference that could still be modified by explicit strategy instructions.

Lastly, Study 3 focused on the impact of individual differences with respect to potential distinctions in dual-retrieval processing of younger and older adults. All previous studies on dual-memory retrieval from a single cue were conducted with younger adults from 18 to 30 years of age. Looking at research that focuses on cognitive processes and changes in memory functioning across the life span, the cognitive processing architecture of dual-retrieval could be different for older adults, that are 50 years and older, than it has been for younger adults. I defined the inspection of age differences in dual-memory retrieval as an assessment of individual factors since age and cognitive slowing might account for processing differences in dual-retrieval practice. Generally, I assumed that each of the three stated factors could have a strong impact on the way individuals engage in the dual-retrieval tasks.

To examine the impact of these factors on the cognitive processing architecture of dual-memory retrieval, the main questions addressed in the present work can be summarized as follows:

i. Examination of task specific factors (Study 1): Are the previous empirical findings by Nino and Rickard (2003) and Strobach et al. (2014) generalizable to new retrieval contexts that incorporate automatized cue response associations, a heightened amount of practice, and different languages? Do the assumptions of the set-cue bottleneck model hold in these new contexts?

ii. Examination of explicit task instructions (Study 2): Can we manipulate the occurrence of specific response patterns by instruction manipulations or are response patterns persistently inflexible?

iii. Examination of individual factors (Study 3): Can the previous empirical findings on dual-memory retrieval from a single cue be generalized from the subgroup of younger adults to older adults? Do the assumptions of the set-cue bottleneck model apply to the cognitive processing architecture of older adults?

SUMMARY OF THE STUDIES

In the following section, I will present the three studies which form the empirical part of this dissertation. Each study will be subdivided into the following parts: Background and research aim, overview of the experiments, and a discussion.

STUDY 1: INVESTIGATING THE BOTTLENECK ACROSS MEMORY DOMAINS: DUAL-RETRIEVAL IN EPISODIC AND SEMANTIC MEMORY

BACKGROUND AND RESEARCH AIM

The goal of Study 1 was to examine the cognitive processing architecture of dual-memory retrieval from a single cue in the context of a new task set and different memory domains. As previously noted, foregoing research on dual-retrieval from a single cue has established results that support the existence of a retrieval stage bottleneck (Nino & Rickard, 2003; Strobach et al., 2014). Even though a number of subjects displayed synchronized response patterns (i.e., grouper subjects) throughout dual-task practice, the bottleneck was shown to persist even after this practice. According to the set cue bottleneck model, the reason why subjects are nonetheless able to display parallel responding is the mechanism of cue-specific chunking that enables the occurrence of learned parallelism. This, in turn, results in synchronized response patterns for practiced cues. Nevertheless, previous research (Nino & Rickard, 2003; Strobach et al., 2014) has only focused on dual-retrieval of novel cues from long-term memory. These studies implemented completely novel cue-response associations which were extensively practiced throughout the experiments. Newly acquired information is rather established to be stored in the episodic memory system (Hutchinson, 2003). Therefore, the cue-response associations that were used can be classified as newly acquired episodic long-term memory traces. Since there have been no investigations on retrievals from other long-term memory domains, it remains an open question if the observed retrieval bottleneck can be classified as a global property of this memory component or if it is only restricted to episodic memory retrievals.

To investigate this open issue, Study 1 used a task modification to include automatized cue-response associations. Automatized associations between words and conceptions are assumed to be stored in the semantic memory system (Hutchinson, 2003). Therefore, this study was able to incorporate two additional and new dimensions: automatized cue-response associations as well as semantic memory retrieval. The new task-set up was generally similar to the previously used task (Nino & Rickard, 2003; Strobach et al., 2014), i.e., it included a vocal response and a manual keypress response. Yet, while previous experiments used color words as cues and digits as the vocal response, the present study incorporated antonym pairs in the vocal task. This means, that the cue words were one part of an antonym pair (e.g., *day*) and the responses were the other part of the pair (e.g., *night*). This part of the task incorporated the automatized cue-response associations, since antonyms have a strong semantic relation and are proven to automatically cue each other in experiments that used semantic priming (Hutchinson, 2003; Lucas, 2000; Perea & Rosa, 2002). To ensure a high level of automatization, all of the antonym pairs in this experiment had a strong forward associative strength, which means that the presentation of the cue word holds a very strong capacity to obtain the response word (Nelson, Dyrdal, & Goodmon, 2005). The other part of the experimental task, the keypress task, was still formed by a new cue-response association: The cue words (i.e., one part of the antonym pairs) were associated with a direction. Therefore, this task was highly comparable to the keypress task in previous experiments (Nino & Rickard, 2003; Strobach et al., 2014).

Including new retrieval cues and a new memory system in the experimental design could have accounted for two different outcomes. First, the new dual-retrieval task with automatized antonym cues could have displayed retrieval patterns that would have been indicative of an absence of a retrieval stage bottleneck. This would have been marked by parallel retrieval even without cue-response practice. It would further support the notion, that the retrieval bottleneck is specific to the retrieval of novel-cue response associations from episodic long-term memory. Second, and contrasting the previous assumption, the retrieval patterns could have reflected sequential processing at the onset of practice and only showed evidence for parallel retrieval (i.e., learned parallelism) after practice for the subgroup of grouper subjects. This result would have supported the presence of the retrieval bottleneck as a global property of long-term memory including episodic and semantic memory retrievals.

Looking into preceding findings from other experiments, some of these discoveries were supportive of the first potential outcome, namely that high automatization is in favor of parallel processing models rather than bottleneck models (Meyer & Kieras, 1997). A few studies investigated the possibility of a bottleneck bypass through task automatization (e.g., Maquestiaux, Laguë-Beauvais, Bherer, & Ruthruff, 2008; Ruthruff et al., 2006). For example, a study by Ruthruff et al. (2006) used the PRP paradigm with two tasks that differed on their level of automatization. The auditory-vocal task of that study was highly practiced and was classified as the high automatization condition whereas a visual-manual task was unpracticed and classified as the low automatization condition. Their results were supportive of a bottleneck bypass for the high automatization condition (i.e., the auditory-vocal task) since most subjects displayed parallel choice processing for this task. In contrast, the low automatization condition (i.e., the visual-manual task) reflected that most subjects used a serial attempt. Another study by Logan and Schulkind (2000) found support for parallel retrieval across semantic memory tasks by evidence of crosstalk between the tasks.

These findings were especially interesting, since they suggested that the assumptions of the set-cue bottleneck model might not hold for the retrieval of automatized cues-response associations. To further investigate the impact of automatized retrievals in the context of dual-memory retrieval, Study 1 provided presumably the first attempt to assess dual-memory retrieval from a single cue with respect to novel versus automatized cue-response associations and across different memory domains. With this study, I focused on the investigation of the cognitive processing architecture of dual-memory retrieval from a single cue in the context of a task modification to assess the role of task specific factors. The study included three separate experiments which focused on the assessment of the response patterns across practiced and unpracticed cues with novel and automatized cue-response associations. This involved a further examination of the assumptions of the set cue bottleneck model within the new task modification as well as a test of extended practice effects by substantially increasing the number of practice triads in Experiment 3. The next sections separately describe the rationale for each experiment in Study 1 and conclude with a summarizing discussion.

Experiment 1: Generalization to a new task set

Experiment 1 specifically focused on the investigation if the results from previous studies (Nino & Rickard, 2003; Strobach et al., 2014) could be extended and probably generalized to a new task set and a new memory domain. Therefore, the general procedure of Experiment 1 of Strobach et al. (2014) was used and modified according to the new cue-response combinations: novel and automatized. If the results would emulate those of Strobach et al. (2014) it could be concluded that the bottleneck, which was observed for the retrieval of novel-cue response associations, would also exist for the combination of novel and automatized cues. According to the findings of Strobach et al. (2014) and the assumptions of the set-cue bottleneck model, it was hypothesized that the results should display RT patterns that reflect sequential retrieval at the onset of practice. It was further hypothesized that parallel retrieval should emerge for a subgroup of subjects during practice. Finally, it was additionally hypothesized that there should be no transfer of learned parallelism to unpracticed (i.e., *new*) cues at the onset of the transfer phase. In contrast, immediate onset of parallel retrieval without practice as well as transfer of parallelism to new cues would have been indicative for the absence of a bottleneck in the retrieval of a combination of novel and automatized retrievals.

The results of Experiment 1 were able to support the notion of a retrieval bottleneck and the set-cue bottleneck model. Further, the results showed evidence for the cue-level chunking account of learned parallelism. Interestingly and in contrast to the previous findings by Strobach et al. (2014) and Nino and Rickard (2003) an individual IRI assessment did not display a significant gap at 300ms which marked the threshold to distinguish between grouper and nongrouper subjects in the previous studies. Moreover, IRIs were generally short and indicative for a synchronized response pattern. According to the short IRIs and the new continuous IRI distribution, no distinction between groupers and nongroupers has been made in this experiment. Instead, the sample was analyzed as a whole. The results of these analyses were indicative for the presence of learned parallelism during practice across the complete sample in Experiment 1. The findings additionally supported the existence of sequential processing at the onset of the transfer phase which fits to the assumptions of a cue-level chunking account of retrieval parallelism, even when novel and automatic associations are presented and thus episodic and semantic memory retrievals are combined, respectively.

Experiment 2: Further testing the assumption of cue-specificity

Even though Experiment 1 supported the cue-level chunking account in the context of the new task modification, the existence of a task-level account could have still been reasonable. Subjects that exhibited synchronized response patterns might have strategically shifted to this response strategy during practice. However, since the transfer phase of Experiment 1 only included *new* cues, the absence of *old* cues might have caused a strategic switch back to a sequential retrieval strategy. This could be caused by the context change in the transfer phase: the absence of old cues creates a new retrieval context which is equal to the context at the beginning of the practice phase. If this assumption would be correct, there would be a *context-dependent task-level account*. To assess this possibility, Experiment 2 included the intermixed presentation of old as well as new cues during the transfer phase. According to the cue-level chunking account, it was hypothesized that the results of the transfer phase should reflect RT2 results that violate the ES prediction on the first transfer triad for old cues, but not for new cues. In opposition, if the context-dependent task-level account would apply, the results of the first transfer triad should reflect the same response patterns and ES prediction violations for old and new cues.

Experiment 2 further supported the presence of a bottleneck as well as the cue-specific account of learned parallelism in the context of intermixed novel and automatized retrievals. Likewise to Experiment 1, the individual IRI analyses did not show evidence for a discontinuation at 300ms or at any other point which would have been indicative for distinct retrieval patterns. Further, the IRIs were mostly short and indicated a synchronized response pattern which accounted for the presence of mostly grouper subjects. While the transfer phase offered a novel study design (i.e., inclusion of old and new cues at the same time) the results were supportive of the previously stated hypotheses and indicated parallel retrieval for old cues, but not for new cues. This assessment provided additional support for the cue-level chunking account of learned parallelism and did not indicate any evidence for a task-level account.

Experiment 3: Increased Practice

While both previous experiments already supported the cue-specificity of learned parallelism in the new experimental task design involving novel, or episodic, and automatized, or semantic, memory retrievals, it remained an open issue if this cue-specificity might be related to the amount of practice. This issue gave rise to the question, if a prolongation in practice might lead to a generalization of dual-retrieval skills that would enable transfer from old to new cues. Therefore, more practice could lead to a switch form cue-specific parallelism to task-specific parallelism. Similar effects were observed across dual-choice RT experiments by Maquestaiux et al. (2008) and Ruthruff et al. (2006). Research from working-memory training further suggests that the amount of practice enables transfer effects to occur and that transfer effects only arise with extensive practice (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008). These results suggested that practice might have a dose-depended impact on transfer effects. To assess the potential of dose-dependency on transfer effects in dual-retrieval practice the amount of practice triads was increased from 15 (i.e., as in Experiment 1 and 2) to 40 practice triads in Experiment 3. In line with the cue-specific chunking account, it was hypothesized that the first transfer triad should have provided evidence for cue-specificity marked by a violation of the ES prediction for old cues but not for new cues. In contrast, if learned parallelism would indeed be task-specific and practice dose-dependent, the results should have been marked by a violation of the lower bound of the ES prediction for old as well as for new cues.

Equal to Experiment 1 and 2, this experiment also displayed a continuous IRI distribution across practice. Therefore, the data was again analyzed across the complete sample. Results from the practice phase provided evidence for learned parallelism in the context of prolonged practice. Further in line with the two prior experiments, the transfer phase supported the occurrence of synchronized responding for old cues, but not for new cues. Conclusively, Experiment 3 exhibited results that were mostly consistent with the assumption of cue-specificity in the context of the set-cue bottleneck model.

Discussion

With Study 1, I was able to provide an additional assessment of dual-memory retrieval from a single cue across a set of new cue-response associations and with different levels of retrieval practice. These results extended the previous support for the set-cue bottleneck model from the retrieval of two novel associations to the combination of novel (i.e., episodic) and automatized (i.e., semantic) memory retrievals. The three experiments were able to extend previous findings (Nino & Rickard, 2003; Strobach et al., 2014) and supplied further evidence for cue-specificity. The results supported the existence of a retrieval bottleneck and the presence of cue-level chunking to exhibit learned parallelism across practice. Taken together, the results were supportive for the presence of a global memory property of the retrieval bottleneck.

As pointed out in the results, none of the three experiments displayed a discontinuity in the IRI distributions. Therefore, subjects were not divided into grouper and nongrouper categories. While the primary analyses showed that the overall data reflected a strong presence of learned parallelism across the whole sample, a more fine-tuned analysis of individual response patterns might be supportive of the presence of individual differences in the response strategies. Hence, an additional set of analyses were conducted to compare the findings from Strobach et al. (2014) to the data in Study 1. In these statistical examinations, the individual observed mean RT2 values for each subject were compared to the mean RT2 values that were anticipated by the ES prediction. In order to ensure that the mean values only incorporated stable response patterns within the individual subjects, the values were averaged over the last 9 practice triads in which the grand mean did not vary or change considerably. The results were visualized by plotting the IRI patterns for each subject and marking the sequential and parallel retrievers. Interestingly, this assessment of Study 1 and Strobach et al. (2014) displayed quite analogous patterns. Namely, that subjects with short IRIs tended to reflect parallel retrieval and subjects with longer IRIs tended to show response patterns that indicated sequential retrieval. However, the results further exhibited that the number of parallel responders was higher in the three experiments presented in Study 1 than in the two experiments by Strobach et al. (2014). The highest number of parallel responders was found in Experiment 3, which involved the most extensive practice. Remarkably, only a very small number of the subjects which were classified as groupers by the 300ms IRI threshold were indicated as sequential responders by the individual level analyses. Equally, the same finding was observed for subjects that were defined as nongroupers by the 300ms cut-off. Only a very small number of them were identified as parallel responders. While these post-hoc analyses need to be treated with caution and should not infer strong causal implications, they still point to the following conclusions. First, the retrieval of two novel versus one novel and one automatized cue-response association does not seem to differ substantially with regard to the dynamics of dual-retrieval and learned parallelism. Second, synchronizing (i.e., grouping) the responses in close proximity seems to be indicative for learned parallelism in the context of dual-memory retrieval across different dual-retrieval contexts. And third, comparing all of the previous and present experiments, their results seem to indicate a potential link between the occurrence of learned parallelism and the amount of practice (i.e., higher levels of practice in Experiment 3 might lead to an increased occurrence of learned parallelism in comparison to the remaining experiments).

To summarize Study 1, it can be concluded that this study found support for the existence of a cue-specific retrieval bottleneck which seems to be a global property of dual-memory retrievals from long-term memory. I was further able to show evidence for learned parallelism in a new task-set and across different levels of practice. Further, while Experiment 1 was conducted with English speaking participants as the initial studies (Strobach et al., 2014; Nino & Rickard, 2003), Experiment 2 and 3 were conducted with German speaking participants, which further showed that the findings can be translated to other languages as well. Therefore, this study was able to generalize and extend the previous studies of Strobach et al. (2014) and Nino and Rickard (2003) to a new task-set which incorporated a new memory domain as well as to a higher amount of practice and a different language context.

STUDY 2: THE IMPACT OF STRATEGY MANIPULATIONS ON DUAL-MEMORY RETRIEVAL

BACKGROUND AND RESEARCH AIM

While the prior studies (Nino & Rickard, 2003; Rickard & Pashler, 2005; Strobach et al., 2014) were able to observe the distinct retrieval patterns of grouper and nongrouper subjects, it remained unknown why some of the subjects adapt synchronized response patterns after practice (i.e., the grouper subjects), whereas others continue to display sequential response patterns throughout practice (i.e., the nongrouper subjects). This has motivated Study 2 to assess if response patterns might be influenced by (1) fundamental individual differences, such as cognitive and functional abilities, or by (2) strategy preferences, such as the preferred choice of a specific response pattern. If the occurrence of both response patterns would be formed by individual differences (i.e., such as potential capacity limitations; Süß et al., 2002), subjects should not be flexible in their response patterns. In contrast, if their responding would be caused by a specific responding preference, this preference could still be flexible and might depend on task demands (Jansen et al., 2016; Sanbonmatsu et al., 2013).

Previous studies have shown that specific instructions, are effective means to generate certain response patterns (Fischer & Plessow, 2015; Levy & Pashler, 2008; Ruthruff et al., 2003). Some of these studies involved experiments that applied the PRP paradigm and instructed their subjects to perform one of the required tasks first. This priority instruction was effective to induce sequential response patterns (Pashler & Johnston, 1998). Further, other researchers have additionally tried to instruct parallel responding by requiring their subjects to evenly allocate their capacity to both tasks (Lehle & Hübner, 2009; Lehle, Steinhauser, & Hübner, 2009). In fact, it turned out that the instructions were effective and that subjects engaged in the instructed response styles. Despite, there are other experiments which lead to the conclusion that subjects are not always able to effectively implement priority instructions (Levy & Pashler, 2008; Miller & Durst, 2014).

An important factor of influence regarding the impact of response instructions might be practice. A study by Jansen et al. (2016) showed that, while they observed a strong response preference in a dual-task paradigm involving an auditory memory task and a high-speed driving task, the response patterns could be changed by instructions. However, this change was only possible after an extensive amount of dual-task practice. As we have seen in previous experiments on dual-memory retrieval from a single cue, practice seems to be an important factor in the development of response strategies (Nino & Rickard, 2003; Rickard & Pashler, 2005; Strobach et al., 2014). Since the adaption of a grouping strategy only happened after practice in the previous experiments involving dual-memory retrieval, the impact of strategy instructions might also be dependent on the level of task practice.

Taking these findings together, it is obvious that there is a need to further examine the occurrence of distinct response patterns to reach a better understanding of the processes that lead to the adaption of each response style. Especially important is an understanding of the development of learned parallelism and an examination of the question if the distinction between grouper and nongrouper subjects is the result of a strategy preference or of an individual difference on a specific functional or cognitive level. To assess these potential accounts, I applied instruction manipulations in a dual-memory retrieval task to assess if instructions are able to effectively influence response patterns or if response patterns are persistently inflexible.

With this study, I particularly focused on the following objectives. In Experiment 1 and 2, the impact of explicit task instructions in dual-memory retrieval from a single cue was tested. Experiment 1 specifically investigated if explicit task instructions could influence retrieval parallelism. Moreover, in Experiment 2, I provided an additional assessment of the cognitive processing architecture of practiced dual-memory retrieval. To further test the assumptions of the set-cue bottleneck model of dual-memory retrieval, Experiment 2 focused on an explicit test of the model's assumptions. To my knowledge, this was the first attempt to empirically investigate the possibility to instruct sequential as well as synchronized response patterns in an experiment involving dual-memory retrieval from a single cue.

EXPERIMENT 1: MODIFICATION OF TASK INSTRUCTIONS

Since this experiment aimed at evoking specific response patterns, a total of three experimental groups were established. In each group, one of the following response instructions was applied: The *neutral instruction*, the *synchronize instruction* and the *immediate instruction*. The *neutral instruction* was the same as in previous experiments (Nino & Rickard, 2003; Rickard & Pashler, 2005; Strobach et al., 2014) and required the subjects to respond as quickly and as accurately as they could. The *synchronize instruction* required subjects to wait until they retrieved both responses from their memory and then to execute them in a synchronized pattern at the same time. In contrast, the *immediate instruction* obligated the first response to occur as soon as the retrieval of it was finished and to execute the second response after the first response execution was finished. These instructions were visually presented on the computer screen and read by the experimenter during the entire practice phase of the experiment before the start of each dual-retrieval block. In the transfer phase, all subjects received the neutral instruction. In correspondence with Experiment 2 of Nino and Rickard (2003) a total of 10 cue-response combinations were used in this experiment across practice and transfer.

In Experiment 1, two main hypotheses were tested. First, I assumed that if the strategy manipulations were effective, results should display a larger amount of grouper subjects in the synchronize instruction group compared to the immediate instruction group. Further, it should be observed that the amount of nongrouper subjects would be effectively larger in the immediate instruction group compared to the synchronize instruction group. Second, Experiment 1 aimed at examining the hypothesis of strategy robustness. Research findings from different cognitive domains led to the hypothesis, that the instructed strategies should be robust, even when subjects would be presented with a neutral instruction after practice (Dembo & Seli, 2004; Jansen et al., 2016, Kramer, Larish, & Strayer, 1995). This means that subjects would further use the instructed strategy even though they could voluntarily choose to use another. This assumption was based on previous studies which have established that strategies are unlikely to change after a lengthy practice (Dembo & Seli, 2004; Kramer et al., 1995). However, it could also be assumed that personal response strategy preferences might overrule the effects of instructions and that subjects would use their preferred strategy when given the chance (Brüning & Manzey, 2018; Fisher & Plessow, 2015; Reissland & Manzey, 2016).

This experiment was able to display evidence for the functionality of strategy instructions to evoke two distinct types of response patterns. As in previous studies, subjects in the neutral instruction group displayed both response patterns: grouping and nongrouping. In the immediate instruction group, all subjects displayed IRI patterns that lead to the classification of a sample that consisted solely of nongroupers. And most subjects in the synchronize instruction condition displayed IRI patterns that classified them as grouper subjects. It was established that all nongrouper subjects in the immediate instruction group indeed displayed sequential processing throughout the whole practice phase. The subjects classified as grouper subjects in the synchronize instruction group showed sequential responding at the onset of practice, however, their RT2 values fell below the ES prediction after the second dual-retrieval block and stayed below throughout the rest of the practice phase. This type of responding was indicative for parallel responding and proved the occurrence of learned retrieval parallelism. Throughout practice, the particular response patterns in the immediate (i.e., nongrouper subjects) and synchronized instruction (i.e., grouper subjects) groups mirrored the response patterns of nongrouper and grouper subjects in the neutral instruction condition, respectively.

The results of the transfer phase were especially interesting. While subjects in the neutral instruction condition still displayed the same patterns as they did during practice, a different picture emerged for the other two instruction groups. Although the strategy instructions were almost seamlessly implemented during practice, the presentation of a neutral instruction during transfer resulted in the occurrence of both, grouping and nongrouping patterns, in both instruction groups. Some of the subjects still displayed response patterns that were equal to the previously instructed patterns. These individuals were classified as strategy stable subjects. In contrast, others switched to a new strategy and were thus categorized as switcher subjects. Interestingly, comparing the IRIs of strategy stable subjects and switcher subjects during the last five practice triads did show a difference between both groups in the immediate instruction group (i.e., switchers already exhibited shorter IRIs during practice right before transfer) but not in the synchronize instruction group.

EXPERIMENT 2: TASK INSTRUCTIONS IN TRANSFER SITUATIONS

After the demonstration of the effectiveness of instruction manipulations to induce two different response strategies during dual-memory retrieval from a single cue, Experiment 2 concentrated on the assessment of the cognitive processing architecture in the context of response strategy instructions. As described earlier, the occurrence of learned parallelism in grouper subjects was assumed to involve cue-specific chunking. Nevertheless, these results were previously only shown in studies which applied a neutral response instruction. It could be assumed that response instructions could influence transfer effects, since the instruction to synchronize responses might enable individuals to chunk even unpracticed cues immediately after practice of the strategy with other cues. If this assumption would indeed be correct, it would provide support for a task-specific account of chunking (or, in the case of this study, an instruction account). Such results would be in direct opposition of the assumptions of the set-cue bottleneck model. More specifically, it would oppose the bottleneck stage of dual-retrieval. Therefore, this experiment focused on a profounder assessment of the assumptions of the set-cue bottleneck model and reached beyond the attempts of previous studies to investigate the processing architecture of dual-memory retrieval.

To perform this assessment, the design of Experiment 1 was modified to include seven old as well as seven new cues. While dual-retrieval trials across the practice phase only included the seven old cues, the transfer phase additionally included the seven new cues (i.e., subjects were presented with all 14 cues in the transfer phase). Further, the practice as well as transfer phase incorporated the continuous use of one strategy instruction, either the immediate or the synchronize instruction. Therefore, the experiment comprised of only two instruction groups. The design of Experiment 2 facilitated a direct test of the impact of instructions on the occurrence of learned parallelism, and therefore the chunking process, in subjects receiving the synchronize instruction. According to the assumptions of the set-cue bottleneck model, it was hypothesized that (1) the application of a synchronize response instruction would not be able to evoke synchronized response patterns for new cues, even after extensive strategy practice with old cues. It was further hypothesized that (2) the immediate instruction should not provide evidence for parallel retrieval throughout practice and transfer.

As in Experiment 1, this study further supported the utility of strategy instructions to effectively initiate response patterns that could be classified as evident for response grouping and nongrouping. Further, also equal to Experiment 1, based on their individual IRI values all of the subjects in the immediate instruction group were classified as nongrouper subjects. They were entirely able to implement the strategy and showed sequential responding across practice (i.e., their RT2 levels started above but merged equal to the ES prediction across practice). In the synchronize instruction condition, most subjects were classified as grouper subjects based on their IRIs. All of these grouper subjects showed RT2 responses that started out above the ES prediction but fell significantly below after the second triad throughout the rest of the practice phase. This result again represented evidence for learned parallelism in subjects that were instructed to engage in synchronized responding. Taken together, the findings of the practice phase of Experiment 2 and its strategy instructions resembled a sound replication of the findings of Experiment 1.

Additionally, the examination of the transfer phase gave a profounder insight into the cognitive processing architecture of dual-memory retrieval. The results in the synchronize instruction group showed that learned parallelism was still present for old cues, but not for new cues. This was marked by RT2 values falling below the ES prediction for the old cues, and by RT2 values being equal to the ES prediction for the new cues. In the immediate instruction condition, there was no violation of the ES prediction for either old or new cues which manifested the presence of sequential responding on the first transfer triad.

These results are supportive of both hypotheses. Mainly, there was no evidence for an elimination of the bottleneck stage of dual-memory retrieval since subjects were not able to perform synchronized response patterns with new cues, even after extensive response strategy practice with old cues and receiving the explicit instruction to synchronize their responses. Further, these results support the cue-level chunking account of the set-cue bottleneck model, since learned parallelism was again shown to be cue-specific rather than task-, or instruction-, specific.

Discussion

While previous experiments with the same task (Nino & Rickard, 2003; Strobach et al., 2014) have been able to observe two distinct response patterns (i.e., sequential and synchronized) that have been naturally chosen by the individuals, Study 2 was able to additionally demonstrate that both patterns could also be efficiently instructed. As Experiment 1 and 2 displayed, instruction manipulations were effective in inducing the use of either synchronized or sequential responding. Therefore, it can be concluded that the occurrence of grouping and nongrouping can be successfully modulated by instruction manipulations. Further, the instructed response patterns were highly comparable to the naturally chosen patterns of grouping and nongrouping in the neutral instruction condition. These findings supported the findings of previous research on instructions in PRP experiments and non-training studies (Laine, Fellman, Waris, & Nyman, 2018; Maquestiaux et al., 2008; Strobach et al., 2012b; Strobach & Schubert, 2017) and extended the knowledge on the effectiveness of instruction manipulations to a dual-retrieval context.

The successful adaption to the instructed strategies clearly speaks against the assumption that response patterns in dual-memory retrieval are based on fundamental individual differences, since the subjects were well able to implement the strategy instructions and therefore showed flexibility in their retrieval patterns. Interestingly, the present results further add to the discussion of strategy preference, given that the results exhibited that several subjects in both instruction groups switched to the opposite strategy during transfer. While findings from different cognitive disciplines have suggested that the instructed strategies should be robust (Dembo et al., 2004; Jansen et al., 2016; Kramer et al., 1995), it could have been assumed that subjects would continuously use the instructed strategy even after the presentation of a neutral instruction during the transfer phase. However, the number of subjects in both instruction groups that switched their strategy during transfer speak against this assumption of strategy robustness and could rather be explained by potential strategy preferences. This means that individuals might have a personal inclination for a specific response style. That result is in line with other dual tasking studies, which also support the possibility that individuals indeed possess distinct response strategy preferences (Brüning, Reissland, & Manzey, 2021; Brüning & Manzey, 2018; Fischer & Plessow, 2015; Reissland & Manzey, 2016), which are adaptable according to task requirements.

Moreover, Experiment 2 provided a robust test of the assumptions of the set-cue bottleneck model of dual-retrieval. Despite the extensive strategy practice and the continuous instruction to use a synchronized response strategy, subjects were not able to perform parallel retrieval for new cues during transfer. This finding supports the notion of a cue-specific chunking mechanism for learned retrieval parallelism which is further in line with the assumptions of the set-cue bottleneck model.

To sum up Study 2, it can be concluded that previous studies on dual-retrieval from a single cue were extended to broaden and advance our understanding of the effects of instruction manipulations and the cognitive processing architecture of dual-memory retrieval. This study supported the notions of the set-cue bottleneck model and supports the presence of a cue-level chunking account of dual-memory retrieval after practice. It further supported the hypothesis, that individual preference, rather than individual differences, moderate the occurrence of either grouping or nongrouping response strategies.

STUDY 3: THE ROLE OF AGE IN THE CONTEXT OF DUAL-RETRIEVAL PRACTICE

BACKGROUND AND RESEARCH AIM

While a large body of research has established the role of aging in the context of the human processing system (e.g., Hertzog, Kramer, Wilson, & Lindenberger, 2009; West, 1996), research on dual-tasking has often focused on younger adults. Especially dual-memory retrieval from a single cue has previously only been researched in the context of adults which were between 18 and 30 years of age (Heidemann, Rickard, Schubert, & Strobach, 2020; Nino & Rickard, 2003; Orscheschek, Strobach, Schubert, & Rickard, 2019; Strobach et al., 2014). To examine if the findings from younger adults could be generalized to older adults as well, Study 3 realized two experiments which included younger (i.e., 19 to 30 years of age) and older (i.e., 55 to 71 years) subjects.

Interestingly, previous studies on the potential difference of older and younger adults with relation to their performance levels have obtained two dissimilar key findings. On the one hand, there were studies which indicated a dual-tasking capacity deficit in older adults (Riby et al., 2004), and on the other hand, no such deficiencies were found (Tun & Wingfield, 1993). An examination of these twofold results displayed that there could be a substantial impact of specific task characteristics, such as the amount of practice, which seems to have accounted for discrepancies across the findings.

Practice has varied largely among the studies investigating dual-tasking in older adults. While studies with a low amount of practice observed larger dual-task costs in older adults compared to younger adults (Verhaeghen, Steitz, Sliwinski, & Cerella, 2003), studies that have used more practice were able to observe a reduction of the performance gap between both age groups (Allen, Ruthruff, Elicker, & Lien, 2009; Maquestiaux, Hartley, & Bertsch, 2004; Strobach et al., 2012b; Strobach, Gerstorf, Maquestiaux, & Schubert, 2015). This means that with practice, older adults were able to compensate for their potential initial deficiency by an increase in speed and accuracy that matched the levels of younger adults. However, even in practice studies, it still remains an open issue who profits more from practice or if both age groups equally benefit from practice (Allen et al. 2009; Bherer et al., 2005, 2006, 2008; Göthe, Oberauer, & Kliegl, 2007; Kramer et al., 1995; Maquestiaux et al., 2004; Strobach et al., 2012b). Besides the impact of practice, a fundamental question was, if the same processing mechanisms that are involved in dual retrieval processing in younger subjects are also involved in the retrieval processing of older subjects (Maquestiaux, 2016; Maquestiaux et al., 2004).

With Study 3, my aim was to further specify the cognitive processing architecture of dual-memory retrieval in the context of two distinctive age groups. Both experiments incorporated a *younger ag*e group (i.e., subjects in an age range from 19 to 30 years) and an *older age* group (i.e., subjects from 55 to 71 years). The findings from these age groups could aid the understanding of the cognitive processing architecture of dual-memory retrieval from a single cue across the stages of early and late adulthood. As in the previous studies, Study 3 focused on the examination of a potential retrieval bottleneck and the presence of learned parallelism within the framework of the set-cue bottleneck model (Nino & Rickard, 2003).

Experiment 1 & 2: Generalization to a New Age Group

The primary goal of Experiment 1 was to examine if previous findings on the cognitive processing architecture on dual-memory retrieval from a single cue that were established in the context of younger adults (Heidemann et al., 2020; Nino & Rickard, 2003; Orscheschek et al., 2019; Strobach et al., 2014), could be replicated in older adults. Results for older subjects could have pointed in two different directions. First, they could have been in line with the response patterns exhibited by younger adults and showed evidence for learned parallelism which would support the set-cue bottleneck model. Second, they could have displayed dissimilar patterns which would be marked by an absence of learned parallelism and therefore might not support the assumptions of the set-cue bottleneck model. Further the evidence for cue-specific chunking could solely be visible in samples of younger adults and not in older adults. Experiment 1 functioned as a replication of Experiment 1 by Strobach et al. (2014) to assess if the previous results could be generalized to older adults. Consequently, the experiment incorporated 7 cues per block during the single-dual practice phase and all 14 cues in the single-dual transfer phase.

To further extend Experiment 1, Experiment 2 included an additional modification to allow for a deeper assessment of potential processing differences between younger and older adults that could be associated with practice. Hence, the procedure was adapted from Experiment 2 of Study 2 (Heidemann et al., 2020) and allowed for increased exposure to all cue-response combinations before the transfer phase: Instead of presenting only 7 cues during all blocks of the single-dual practice phase, 14 cues were presented in the single-retrieval blocks of the single-dual practice phase. The dual-retrieval blocks still incorporated only 7 of the cues during the practice phase. In that prior experiment (Heidemann et al., 2020), the increase of cues presented during the single-retrieval blocks during practice did not influence the response patterns. I was still able to observe learned parallelism and found evidence for cue-specific chunking. However, this could be different for older adults. It could be, that older adults might not be able to exhibit parallel retrieval in this new experiment, due to the increase of cues and therefore the increase in task demands, which could hinder them in their dual-retrieval capacity. On the contrary, while younger adults exhibited sequential retrieval at the onset of transfer with new cues, it could still happen that older adults might not show this switch and are able to perform parallel retrieval for new cues which has not been shown in younger adults.

Across both experiments, both age groups were able to increase the speed of their RTs during practice. According to the 300ms IRI cut-off for the distinction between grouper and nongrouper subjects (Nino & Rickard, 2003), subjects in the younger age groups in each experiment were divided into both categories. Though, in both experiments the group of older adults exhibited significantly longer RTs and especially RT2s than the group of younger adults, the 300ms threshold had to be modified to accredit for the distinct RTs of older adults. To account for this, a slowing factor was established in each individual experiment by dividing the averaged mean IRI of the older adults group by the averaged mean IRI of the younger adults group. According to this new IRI classification, in each experiment, the amount of grouper and nongrouper subjects did not differ significantly between both age groups.

Within both experiments, analyses of the practice phase showed evidence for sequential responding across the nongrouper subjects in both age groups. For grouper subjects, initial sequential responding was observed in the younger as well as in the older adults group. Equal to previous findings, RT2 fell significantly below the ES prediction which provided evidence for parallel responding and learned retrieval parallelism in both age groups.

For nongrouper subjects, transfer results revealed the presence of sequential responding for both, younger and older subjects. This result was evident for both age groups and across both cue-types (i.e., old and new cues). For grouper subjects across both age groups, there was evidence for parallel responding on old cues on the first transfer triad. Equal to previous findings, RTs for new cues were indicative of sequential responding on the first transfer triad. Taken together, these results are generally supportive of the cue-level chunking account and indicate no differences in the processing mechanisms between younger and older adults.

DISCUSSION

Altogether, I was able to observe supporting evidence for learned parallelism and the cue-specific chunking account across two adult age groups. However, there seemed to be differences between younger and older adults regarding their response speed: the increase of cue-presentations during single-retrieval blocks in the practice phase of Experiment 2 seems to have moderated RTs for older adults (i.e., by showing significantly longer RTs than younger subjects). Despite the slowing of older adults, both experiments indicated no general differences between younger and older adults in the processing of the dual-retrieval task. This result points to the presence of the same structural processing architecture of dual-memory retrieval from a single cue across both age groups. Therefore, the decrease of response speed in older adults from Experiment 1 to 2 seems to be rather influenced by task-related factors which seem to have a differential impact on younger versus older adults.

As stated above, task-specific factors seem to have had an impact on the results. Looking into the task specific factors that were changed from Experiment 1 to 2, the amount of practice in Study 3 (i.e., the number of practice triads) was not in- or decreased from Experiment 1 to 2. Though, the number of cues was doubled in the single-retrieval blocks. This increased the complexity of the retrieval task. The evident slowing of older adults in Experiment 2, might have been influenced by the increased task complexity in this experiment. This outcome is underlined by other findings which have found support for an influence of task complexity on the performance differences between younger and older adults which was independent of practice (Luo & Craik, 2008; Maquestiaux et al., 2004).

Previous studies concluded that older adults' capacity to engage in parallel processing would be qualitatively different to younger adults, marked by an incapacity to perform parallel retrieval (Göthe et al., 2007; Maquestiaux, 2016). Yet, both experiments from Study 3 showed that there were no differences between younger and older adults in their response patterns and processing of the dual-task. Further, older adults were able to display a grouping strategy and showed evidence for learned retrieval parallelism. Therefore, while age indeed influences the processing speed in dual-retrieval tasks, marked by longer RTs for older adults (Hartley & Little, 1999; Maquestiaux, 2016; Maquestiaux et al., 2004), it does not mark structural differences in the processing architecture. Moreover, the present results let me conclude that the bottleneck in dual-memory retrieval seems to be unaffected by age and that there does not seem to be a qualitative difference in the processing of dual-memory retrieval from a single cue between younger and older adults. Like younger adults, older adults also displayed evidence for the capacity to engage in cue-specific chunking.

Conclusively, I was able to provide support for the assumptions of the set-cue bottleneck model in the new context of older adults. Both, younger and older subjects, displayed evidence for learned parallelism and provided support for the cue-specific chunking account. All in all, Study 3 was able to show the stability of the structural mechanisms of the cognitive processing architecture of dual-memory retrieval after practice across younger and older age.

General Discussion

The goal of the present work was to examine the cognitive processing architecture of dual-memory retrieval after practice. This investigation was mainly focused on the exploration of three factors which have been studied and discussed in the previous empirical section of this work: task specific factors (Study 1), explicit task instructions (Study 2), and individual factors (Study 3). Study 1 assessed whether previous findings on the processing architecture of dual-memory retrieval after practice from a single cue (Nino & Rickard, 2003; Strobach et al. 2014) could be generalized to a new retrieval context with automatized cue-response associations. Study 2 examined if it would be possible to manipulate the occurrence of specific response patterns (i.e., sequential vs. synchronized patterns) by instruction manipulations or if responding would be inflexible to manipulations. Lastly, Study 3 dealt with the examination, if the previous assumptions on dual-memory retrieval from a single cue could be generalized from the subgroup of younger adults to older adults as well. Further the underlying main subject of all associated studies was, whether the set-cue bottleneck model, and its associated assumptions, is a sufficient and an adequate model to assess and describe the processing architecture of dual-memory retrieval from a single cue.

In this section I will link and discuss the findings from my empirical research and give an outlook for future research in this field. First, I will discuss the interplay and connection of the three main factors examined across the single studies. Then, I will discuss my findings with respect to their implications on the set-cue bottleneck model of dual-memory retrieval.

Consequences for the cognitive processing architecture: The interplay of Three Factors of Influence

Looking into Study 1, I was able to generalize the previous findings by Nino and Rickard (2003) and Strobach et al. (2014) to a new retrieval context. Whereas the previous studies examined the retrieval of two newly established responses from episodic memory, I was able to extend and generalize these findings to the combination of one novel (i.e., episodic) and one automatized (i.e., semantic) memory retrieval. All three experiments of Study 1 were generally able to support the cue-level chunking account of learned retrieval parallelism. Interestingly and contrary to the previous studies (Nino & Rickard, 2003; Strobach et al., 2014), there was a larger number of participants that were displaying synchronized responding. This finding is interesting, since it supports the notion that task related factors, such as the modification of memory domains involved in the retrieval task, seem to have an impact on dual-memory retrieval from a single cue.

In detail, the finding of a heightened amount of grouper subjects in Study 1 is especially noteworthy, since the experiments did not involve specific instructions on how to respond, besides the general neutral instruction to respond as fast and as accurately as possible. Nevertheless, the majority of subjects displayed grouping behavior and showed evidence for learned retrieval parallelism. This raised the question why the results did not reflect a more balanced mixture of grouper and nongrouper subjects as previous experiments did (Nino & Rickard, 2003; Strobach et al., 2014). Since Study 1 applied a new task design to involve retrieval from semantic as well as episodic memory, the task requirements were changed due to the engagement of two different memory domains. This, in turn, could have caused an overall tendency to engage in grouping behavior. A reason for this might be the interplay between episodic and semantic memory. While two completely novel associations retrieved from episodic memory (Nino & Rickard, 2003; Strobach et al., 2014) did show an even distribution between participants using grouping and nongrouping strategies, the combination of one novel association from episodic memory and one automatized association from semantic memory has facilitated the engagement in a grouping strategy. There thus seem to be differences in the processing of two retrievals from the same memory system versus two different memory systems. This finding also shows that learned parallelism, and therefore a parallel retrieval processes, could either be catalyzed or probably retained depending on the memory systems involved in the task. Therefore, Study 1 was able to display that a modification of task related factors was able to change the amount of specific response patterns. In particular, the engagement of episodic as well as semantic memory retrievals seems to have facilitated the emergence of parallel processing in the sense of learned parallelism. This further shows that the proposed bottleneck is not solely apparent in the specific task-set up of two retrievals from the same memory domain, but instead the results of Study 1 support the presence of a global structural bottleneck in the framework of the set-cue bottleneck model.

Additionally looking into the role of memory with regard to its interplay with individual factors (i.e., such as age) previous research suggested that, compared to younger adults, older adults exhibit impairments in episodic memory retrievals under dual-tasking conditions (Bucur et al., 2008; Glinsky, 2007; Riby et al., 2004). No such discrepancy between both age groups was observed for semantic memory retrievals in dual-task settings (Light, 2000; Wingfield & Kahana, 2002). These findings were further supported by a study on age-related cognitive decline which observed a deficit for episodic but not for semantic memory retrievals in older adults (Riby et al., 2004). Interestingly, while the task design used in Study 3 can be considered to be focused on episodic memory retrievals, there was no support for a deficit in the dual-retrieval capacity of older adults for the case of two retrievals from a single-cue.

Even though the cue-response associations in the present experiments can be classified as involving episodic memory retrieval, according to the set-cue bottleneck model, a working memory process is assumed to play the critical role in cue-specific chunking (Nino & Rickard, 2003; Strobach et al., 2014). Taking the role of working memory into particular account, the results of Study 3 are further in line with findings from a recent meta-analysis (Jaroslawska & Rhodes, 2019), which discussed that deficits in older adults' capacity to store and process concurrent tasks in working memory seem to be affected by the adjustment of the level of demand of each task before the tasks are combined in a dual-retrieval setting. It might be that the extensive practice on single-task retrievals in Study 3, as well as the use of only one cue for dual retrieval, eliminates the need to select and discriminate between two presented cues. This could be one potential candidate explanation for the absence of age differences in the processing mechanisms between younger and older adults across both experiments in Study 3, since their response processing might have been influenced by the concurrent requirement of a storage and processing demand in working memory (i.e., which can be defined as associated with the process of chunking). This is in line with studies on chunking which have shown that, while older adults seem to take more time to develop chunking behavior, practice is able to eliminate age differences in chunking abilities (Barnhoorn, Van Asseldonk, & Verwey, 2019). That further adds to the influence of practice as a factor that is able to account for a reduction of performance differences between older and younger adults (Allen et al., 2009; Maquestiaux et al., 2004; Strobach et al., 2012b; Strobach et al., 2015).

The data of Study 3 further contributes to a clearer understanding of the relationship between individual factors and task related factors. The individual factor, age, did not show an impact on the cognitive processing architecture. However, certain task related factors (i.e., higher task demands) seem to have an impact on individual factors. This means that while dual-retrieval processing in younger adults does not seem to be influenced by the increase of task demands and an increase in the cognitive load, older adults seem to be affected by that. This was shown by (1) the longer RTs observed in older adults, especially in Study 3's Experiment 2 and (2) the need to adapt a slowing factor to correctly identify the processing mechanisms in older adults, which would have been otherwise masked by the generally slower responding of older adults. While older adults were well able to adapt to the process of learned parallelism, they seem to be affected more by the increase of task demands. While the chunking process of these older adults might take longer, due to working memory constraints (Craik & Bialystock, 2006; Park et al., 2002), younger adults did not show any effect that could have been influenced by the increased task demands. Although the structural processing components appear to be the same in the context of the set-cue bottleneck model, the present results from Study 3 add to the finding of a reduction in processing speed among older adults (Eckert, 2011; Luo & Craik, 2008). However, their apparent reduced working-memory capacity (Craik & Bialystock, 2006; Park et al., 2002) does not inhibit them to engage in parallel retrieval processing.

While Study 1 and 3 have provided evidence for the influence of changes in task related factors on dual-memory retrieval performance as well as the impact of individual factors such as age, Study 2 was able to further investigate the impact of task related factors on a separate level, by examining the impact of strategy instructions. According to the findings from Study 2, people seem to have an individual strategy preference. This result is further in line with the findings from other dual-tasking research (Brüning & Manzey, 2018; Fischer & Plessow, 2015; Reissland & Manzey, 2016) that established similar support for the presence of strategy preferences. However, as far as Study 2 established, preferences are shown to be adaptive to task requirements, such as strategy instructions. The study further showed, that both types of strategies (parallel vs. sequential) can be induced efficiently and that there is no capacity limit or fundamental difference between individuals that allows certain people to engage in parallel processing while others could not. Even though some participants switched to another strategy (i.e., switcher subjects) in the transfer phase, they were able to follow the strategy instructions and to efficiently implement either response style without compromising on speed or accuracy, since the instructed response patterns did mirror those that were obtained in the sample that received a neutral strategy instruction (i.e., naturally appearing grouper vs. nongrouper subjects). These findings are generally in line with studies from other dual-tasking domains such as PRP designs (Lehle & Hübner, 2009; Lehle et al., 2009) and applied designs (Jansen et al., 2016), which supported the efficiency of strategy instructions. Further, they are generally not supportive of studies which suggested potential capacity limitations marked by fundamental individual differences that could lead to the adaption of only one response style (Süß et al., 2002).

In that sense, while grouping and nongrouping strategies seem to be influenced by an individual factor of preference (i.e., as in Study 2), the present work was able to support the notion that task specific factors like differential retrieval contexts (e.g., such as novel vs. automatized cues; Study 1), or specific strategy instructions, are able to modify the way people engage in dual-memory retrievals from a single cue. What can be concluded is, that it is not only one factor, but a complex interplay of task related factors, individual factors and specific task instructions that can alter the amount and occurrence of specific retrieval strategies. Despite these influences, I was able to observe stability in the cognitive processing architecture of dual-memory retrieval from a single cue, which I am going to discuss with respect to the set-cue bottleneck model in the following section.

Implications for the set-cue bottleneck model of dual-memory retrieval

One of the main goals of the present work was to test and assess the assumption of the set-cue bottleneck model of dual-memory retrieval. While I previously discussed the factors that were found to impact the two different processing styles observed across the three present and previous (Nino & Rickard, 2003; Strobach et al., 2014) studies, I will now discuss the implications for the theoretical framework. The most predominant finding was that the cognitive processing architecture of dual-memory retrieval from a single cue can indeed best be explained by the proposed set-cue bottleneck model. Across all three studies and equal to the findings of Nino and Rickard (2003) as well as Strobach et al. (2014), retrieval at the onset of practice was found to be strictly sequential. Just looking at the practice data of sequential retrieval subjects (i.e., nongroupers), I could assume two different notions: While the finding of solely sequential retrieval could generally support the notion of a capacity constraint in the form of a bottleneck, it could have also just been the strategic choice to engage in a sequential retrieval pattern and does not provide any test of the underlying processing architecture. In contrast to that, the occurrence of grouper subjects enabled the assessment of the potential bottleneck. Throughout all three present studies, I was able to observe the emergence of synchronized response patterns by grouper subjects. Most importantly, and fully in line with the assumptions of the set-cue bottleneck model, was the finding that this type of processing did only occur after practice. On a group level, there was no support for parallelism at the immediate onset of dual-retrieval practice, even though all cue-response combinations have been thoroughly practiced under single-retrieval conditions prior to the start of the dual-retrieval practice. Consequently, dual-retrieval practice particularly seems to be required for the emergence of learned retrieval parallelism. Isolated single-retrieval practice does not account for the emergence of joint activation of both set cue nodes and the development of chunking. This is additionally supported by the findings from the transfer phases that were applied across the present studies. Even though cue-response combinations were practiced up to a level of potential automatization and established long-term memory connections, subjects were not able to exhibit parallelism at the start of the transfer phases. This supports the notion of cue-specificity in chunking at the individual cue-response level and does not support a task-general account, which would have proclaimed that parallelism is not limited to specific cue-response associations but rather to the practice of the dual-retrieval task per se.

Adding to this point, the results of Study 2 show that, while parallel responding was able to be effectively instructed, participants were not able to perform parallel retrieval either at the onset of practice, or at the onset of the transfer phase for new cues, after extensive practice has taken place. This finding provides strong support for the presence of a structural bottleneck and opposes assumptions of a strategic bottleneck that could be eliminated with differential task manipulations (i.e., such as extensive practice or simple ideomotor compatible tasks) (Maquestiaux, Lyphout-Spitz, Ruthruff, & Arexis, 2020; Maquestiaux, Ruthruff, Defer, & Ibrahime, 2018; Meyer & Kieras,1997; Schumacher et al. 2001).

I was further able to find support for the set-cue bottleneck model of dual-memory retrieval in the context of the new retrieval context introduced in Study 1 (i.e., highly automatized antonym pairs and novel cue-response associations). Even for the combination of one novel and one automatized retrieval, only practice was able to establish the occurrence of parallel responding, which further supports the assumption of learned parallelism. While the dual-memory retrieval task used in the present studies generally provides an advantage compared to designs that are using two different cues, by reducing task-interference and levels of divided attention (Fagot & Pashler, 1992), it has additionally been established that a lower level of resource competition can lead to better performance in the sense of more efficient multitasking (Göthe et al., 2016; Schaeffner, Koch, & Philipp, 2018). This could have accounted for the heightened amount of grouper subjects across the experiments in Study 1, compared to the other studies in this work, since the task design might have enabled the subjects to adapt more easily to a parallel retrieval strategy, which has further been proposed as posing less mental effort than sequential responding (Hull, 1943; Kool, McGuire, Rosen, & Botvinick, 2010).

Additionally, the present results support the assumptions of the set cue-bottleneck model across older adults as well. While Study 3 adds to the body of research that has thoroughly established age differences based on cognitive slowing of older adults (Hertzog et al., 2008; West, 1996), which has been manifested in longer RTs in Study 3 as well, older adults do seem to have the structural capacities to engage in cue-specific chunking and to exhibit learned retrieval parallelism. This implies that older subjects do not seem to have a more rigid bottleneck, since they also exhibited the capacity to develop chunking. However, certain task components which increase the demand of higher order processing might be influencing the effort and time that is needed for older adults to develop learned parallelism.

Hence, even though I was able to display that humans generally have the cognitive capacity to engage in either sequential or parallel responding (Study 2), there are certain factors that promote a heightened level of parallel responding. Factors that promote, or facilitate, parallel retrieval strategies are: practice, highly overlearned (automatized) cue-response associations (such as antonym pairs), and specific instructions. Now, it could be generally argued that parallel responding is not equivalent to parallel retrieval, however if we would mainly observe choice based parallel responding, we would also be able to observe this kind of responding on the first transfer triad after practice. However, since participants were overall not able to provide parallel responding on the first transfer triad, even after the specific instruction to do so, it can be concluded that learned parallelism is associated with at least some form of parallel retrieval.

Taken together, while I illustrated differential impacts of several factors on the performance of dual-memory retrieval after a single cue, the underlying retrieval processes seem to be unaffected by task modifications or individual factors. Though the bottleneck of dual-retrieval might not hold for other tasks and could be potential bypassed in different dual-tasking designs that have solely focused on working memory performance (for example in simple ideomotor tasks in the PRP context as in Maquestiaux et al. 2020; 2018), it seems to be essential in the retrieval process of dual-memory retrieval from a single cue in the context of long-term memory retrievals. In fact, my results are highly supportive of the assumptions of the set-cue bottleneck model. Proving it to be an effective model to describe the processes involved in dual-memory retrieval from a single cue after practice and helping to specify the cognitive processing architecture associated with parallel retrieval.

Research outlook

Looking at future directions to additionally assess and examine the structural basis of the bottleneck in dual-memory retrieval, research could be able to further specify and modify dual-retrieval models in accordance with potential imaging data. While there have been imaging studies on dual-tasking which have suggested that specific brain structures, such as cortical structures, play a crucial role in dual-tasking (Verghese, Garner, Mattingley, & Dux, 2016), mapping the functional activation during dual-memory retrieval would help to develop more neural network models (Recanatesi, Katkov, Romani, & Tsodyks, 2015). More knowledge on the neural activation during dual-memory retrieval could further assist the development of more precise computations of the exact processes that occur during the retrieval processes and potentially help to further specify the mechanisms that are involved in the development of cue-specific chunking.

More fine-tuned approaches on the level of computational models in the sense of predicting response patterns could mark efficient dual-retrieval strategies and could potentially assess more distinct types of dual-memory retrieval. When we look at the predicted data by the ES model and the observed data for nongrouper subjects, the theoretical modelling of the data was found to be highly overlapping with the observed data providing further support for this assessment method to quantify and qualify computational concepts to assess the differences in cognitive processing. However, it could be of further use to establish more modelling approaches that could lead to a better distinction between grouper and nongrouper subjects. While the previously approached IRI threshold (Nino & Rickard, 2003; Strobach et al. 2014) was marked by a gap at 300ms in these studies, the present studies were not able to find such a distinct gap. Instead, the present data did find more continuous patterns. Study 2 was able to show that the RTs and IRIs of instructed patterns mimic those that were naturally occurring without a proposed strategy and provided more empirical support for the 300ms distinctions. Even though, the threshold needed to be adapted for older adults to correctly identify the processing strategies. Therefore, future research could focus on markers that would lead to a more theoretically driven distinction between both retrieval subgroups. In that sense, imaging data could help to find more distinct markers such as specific event related potentials.

Moreover, future research could focus on further examining the assumptions of the set-cue bottleneck model in task designs that adapt further strategy instructions across heightened practice to account for more systematic tests of the possibilities of potential bottleneck bypasses that have been observed in other task designs and to further examine the differences between dual-tasking in long term vs. short term memory. This could lead to a better understanding of potential difficulties that arise in the heightened amounts of multitasking situations in the daily life (Cardoso-Leite, Green, & Bavelier, 2015). Here, it could be central to look further at dual-tasking strategies and their application in the workplace: Jobs that require multitasking could be optimized by increased efficiency and maybe also by decreased mental effort. Personal strategy preference might not be the most efficient choice in the instrumentalization of multitasking situations and instead performance could be less demanding by using appropriate instructions in dual-task situations. Therefore, understanding the basic principles of human cognition is the most effective tool to help and aid human cognition and human behavior.

Conclusion

The present dissertation examined the cognitive processing architecture of dual-memory retrieval from a single cue after practice. Within this work, I identified the interplay of task related factors and individual factors in the processing of dual-memory retrieval. I was able to generalize previous findings by Nino and Rickard (2003) and Strobach et al. (2014) to the new retrieval context of automatized cue response associations, to a new age group and to test the assumptions of the set-cue bottleneck model within these scenarios as well as with explicit strategy instructions. In conclusion, I demonstrated the occurrence of learned retrieval parallelism across several studies and found compelling support for the assumptions of the set-cue bottleneck model of dual-memory retrieval.

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