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A multitasking perspective on sequence representations and multimedia learning

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A multitasking perspective on sequence representations and multimedia learning

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Abstract

This habilitation thesis (17 articles) uses multitasking to understand how the mind works. Utilizing basic lab experiments as well as applied research the articles of this thesis examine the interplay of representations and the processes which operate upon them. The basic lab experiments (Articles 1 to 10) revealed that the human cognitive system employs various sources (e.g., fixed serial order) to predict upcoming stimuli and responses. It automatically integrates two tasks into one, which can be the reason for dual-task costs. The applied learning experiments (Articles 11-17) used the assumption that dual-task interference can occur in the human operating system when two tasks compete for the same mental resources (e.g., deterioration in postural control can be due to high cognitive load). Moreover, methodological approaches developed in basic multitasking research can be adopted to study information processing in applied settings. For instance, the switching costs approach was adopted from task switching to examine graph comprehension. It suggests that the human cognitive system can extract information from graphs based on a hierarchical structure with several invariant common schemas and underlying specific schemas. Taking all of this into account, this thesis exemplifies that multitasking can be used as a window into the mind. It extends our knowledge on cognitive structure, flexibility and plasticity of the mind.

Keywords: multitasking, representations, sequence learning, prediction, task integration, cognitive capacity, multimedia
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1. Introduction

1.1. Multitasking as a window into the mind

For over a century, cognitive psychologists have been trying to understand how the mind works with respect to representations and the processes that operate on the basis of these representations (e.g., for a review, see Kleinsorge, 2021). The aforementioned processes often contain perception, response selection and execution based on given stimulus–response mappings (e.g., Hübner & Druey, 2006). Since the early nineteen-hundreds (Ach, 1910), experimental psychology research has been documenting how highly flexible and efficient the human mind is. We can shield our mental processes from the associative strength of long-term memory entries (i.e., semantic pair associate) and set filters to accommodate the requirements of a situation (i.e., find a rhyme). In other words, we can flexibly self-program our mind to adapt to situational demands. Therefore, an essential question in cognitive psychology is how the mind processes these representations based on stimulus–response rules (Anderson & Lebiere, 1998; Pinker, 1997). As the mind cannot be inspected directly, the processes must be inferred from observations.

Multitasking (synonym of dual-tasking) is a research area that has been especially productive in detailing the interplay of representations and the processes that operate upon them (e.g., for reviews, see Koch et al., 2018; Künzell et al., 2018; Strobach et al., 2018). Given the multi-faceted empirical contributions on experimental effects in dual-tasking (i.e., psychological refractory period, Pashler, 1984; Welford, 1952) or task switching (i.e., switch costs, Rogers & Monsell, 1995), one might intuitively think that research in cognitive psychology on multitasking is only about performing multiple tasks. Yet I would like to argue that this impression is most often misleading and incomplete. Rather, multitasking setups provide a unique window into the interplay of representations and the processes operating upon them. For instance, one can argue that the core of empirical studies on task switching (e.g., Kiesel et al., 2010; Meiran, 2000; Monsell, 2003; Rubinstein et al., 2001) is not as much about how we switch from one task to the other (e.g., switch rules between categorizing numbers as even or odd, and categorizing numbers as larger or smaller than five) as it is about how representations are activated and deactivated across repeated vs. switched trials. In multitasking, the concurrent performance of two or more tasks overburdens the human cognitive system. Multitasking can thus be a highly infor-
1. Introduction

Formative tool, unraveling how the cognitive system operates by encumbering its limited processing capacities (cf. Baddeley & Hitch, 1974). Accordingly, this thesis examines the interplay of representations and the processes operating on these representations by using multitasking in basic and applied research.

1.2. Basic research

Articles 1 through 10 focus on whether and how sequential representations in multitasking can be acquired and used in basic research. This series of experiments mainly adopted the Serial Reaction Time Task (SRTT), which is a typical setup used to detect how the representations of a series of stimuli and responses are acquired (for a review, see Abrahamse et al., 2010; Nissen & Bullemer, 1987; Schwarb & Schumacher, 2012). In this setup, participants see a target at one of four possible target locations on the screen. Each location is mapped to a response key. Through many repeated trials, participants are to press a response key matching the current stimulus position as quickly and accurately as possible. The sequence knowledge can be measured using the response time (RT) differences between blocks containing the practiced repeating stimulus as well as the corresponding response sequence and blocks with random or otherwise altered stimuli and response sequences (Klein, 2000; Mayr, 2009; Vaquero et al., 2006). In a series of experiments, various types of representations were examined under multitasking, such as serial order (e.g., the order of four target positions), timing (e.g., delay of the four target positions), and movements (e.g., muscle activities in arms). The results suggested that participants can acquire and use various types of sequence representations (cf. Clark, 2019; Gregory, 1980; von Helmholtz, 1860). These are gathered and applied to form predictions as well as prevent dual-task costs (i.e., differences between performing a single task and two concurrent tasks, Pashler, 1994).

1.3. Applied research

Most basic research in multitasking adopts simple tasks to examine the limits of cognitive capacity and task representations (e.g., Hazeltine & Teague, 2002; Logan & Gordon, 2001; Meyer & Kieras, 1997a). Yet laboratory setups with simple tasks are inadequate to ensure that the obtained results are also valid for complicated tasks. Articles 11 to 17 deal with the question of whether and how representations like texts and pictures are acquired and used in the context of multitasking. This series of experiments used the assumption that during multitasking operating processes share
1.4. Thesis structure

This thesis aims to use multitasking as a window into the mind and scrutinize the interplay of representations and the processes operating upon them. Section two introduces studies in basic laboratory research with highly controlled experimental setups (Articles 1-10). Section three introduces studies in applied research on multimedia learning (Articles 11-17). Section four discusses the benefits of multitasking as a window into the mind compared with single tasking and cognitive training research. It also includes suggestions for future studies as well as educational implications.

Seventeen articles have been published in or submitted to international peer-reviewed journals (see Table 1.1). Of these, 10 are first-author articles and 7 are co-author articles. Thirty co-authors are Bachelor and Master students, as well as internal and external colleagues from various disciplines, such as psychology, education, statistics, and sport sciences. The articles include 36 experiments, which were programmed using various software, such as E-prime, Lazarus, Psychopy, R Shiny, Unipark, and the Tobii eye tracker environment. Quantitative data were collected, such as RT, error rate, response accuracy, eye movements while performing the task. In addition, most articles in this habilitation thesis follow the guidance of Open Science Practices (Open Science Collaboration, 2015).
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<thead>
<tr>
<th>Articles / No. of Exp.</th>
<th>Main question</th>
<th>Type of stimulus and task</th>
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<tbody>
<tr>
<td>1. Brocker et al. 2017</td>
<td>Literature review on prediction in multitasking</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>Lack of research on prediction in multitasking.</td>
</tr>
<tr>
<td>2. Gaschler et al., 2018 / 2 Exp.</td>
<td>Can prediction of cueing and serial order be used in multitasking?</td>
<td>SRTT; two-choice visual-manual task</td>
<td>Single vs. multitasking; sequence vs. random block; position in quadruple</td>
<td>RT, error rate</td>
<td>Cueing and serial order can be used in multitasking.</td>
</tr>
<tr>
<td>3. Zhao et al. 2018 / 3 Exp.</td>
<td>Do two forms of representation of serial order (i.e., chaining and ordinal position) influence speeded typing under multitasking?</td>
<td>Speeded typing; tone counting/identification task</td>
<td>Single vs. multitasking; Subsequent words overlap (no overlap vs. chaining vs. chaining and ordinal position vs. full overlap); words vs. pseudo-words</td>
<td>Word completion time, latency of first keystroke, inter-keystroke interval</td>
<td>Slower response in partially overlapped subsequent words than full and no overlap. Words are processed as chunks with slow response to first letter and fast responses to the following letters. The impact of dual-tasking was weak on speeded typing.</td>
</tr>
<tr>
<td>4. Zhao et al. 2019 / 2 Exp.</td>
<td>Can sequence of stimuli and responses (what) and the sequence of SOA (when) be learned and used in multitasking?</td>
<td>SRTT; two-choice visual-manual task</td>
<td>Sequence vs. random block; SOA (200 vs. 500 ms); Timing vs. stimulus</td>
<td>RT, error rate</td>
<td>Stimulus and timing sequences can be learned and they are used independently in multitasking.</td>
</tr>
<tr>
<td>5. Aufschnaiter et al., 2021 / 3 Exp.</td>
<td>Can humans associate three events to three different predictive pre-target intervals?</td>
<td>Foreperiod (FP) paradigm</td>
<td>FP duration; frequency of FP; arithmetic vs. geometric vs. average of both</td>
<td>RT, error rate</td>
<td>Humans can associate three events to three different predictive pre-target intervals. Different timing representations can be active in the same task context.</td>
</tr>
<tr>
<td>6. Röttger et al., 2019 / 4 Exp.</td>
<td>Why does adding a task with random stimulus and response sequence to a SRTT task hinder sequence learning?</td>
<td>SRTT; tone task</td>
<td>Sequence vs. random block; spatial vs. arbitrary; single vs. multitasking</td>
<td>RT, error rate</td>
<td>The detrimental effect is due to task integration of the SRTT and tone-task.</td>
</tr>
<tr>
<td>7. Röttger et al., 2021 / 3 Exp.</td>
<td>Why is sequence learning impaired in multitasking?</td>
<td>SRTT; tone task</td>
<td>Sequence vs. random block; single vs. multitasking; frequent vs. infrequent trials</td>
<td>RT, error rate</td>
<td>Participants tend to integrate the events belonging to the two different tasks into one single sequence.</td>
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## 1.4. Thesis structure

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</thead>
<tbody>
<tr>
<td>Zhao, Gaschler, Nöhring et al., 2020 / 2 Exp.</td>
<td>Can across-task integration explain why sequence learning is impaired in multitasking?</td>
<td>SRTT; two-choice visual-manual task</td>
<td>Sequence type (random vs. fixed sequence vs. ordinal position random); congruency vs. prior congruency</td>
<td>RT, error rate</td>
<td>Response location variability of sequence learning in SRTT can be a relevant measure for sequence learning.</td>
</tr>
<tr>
<td>Zhao, Gaschler, Kneschke et al., 2020 / 1 Exp.</td>
<td>Which types of memory loads are involved in the acquisition and execution of Origami folding?</td>
<td>SRTT on a touchscreen; shutting down the tone task</td>
<td>Block of practice; sequence vs. random; sequence vs. multitasking</td>
<td>RT, error rate; deviation of response position in % panel size; explicit sequence knowledge</td>
<td>Explicit group acquired the sequence in multitasking. Muscle activity can be a useful indicator for sequence learning.</td>
</tr>
<tr>
<td>Leh et al., 2022 / 1 Exp.</td>
<td>Can muscle activations via electromyography (EMG) indicate sequence learning in multitasking?</td>
<td>SRTT; two-choice visual-manual task</td>
<td>Sequence vs. random; block; group (implicit vs. explicit)</td>
<td>Premotor time; error rate; EMG integral after response onset</td>
<td>Explicit group acquired the sequence in multitasking. Muscle activity can be a useful indicator for sequence learning.</td>
</tr>
<tr>
<td>Zhao, Gaschler, Kneschke et al., 2020 / 1 Exp.</td>
<td>Can distance to screen indicate high cognitive load in multimedia learning?</td>
<td>Multimedia learning; postural control</td>
<td>Reading condition (question after vs. before material); 5 quintiles of reading; head-to-screen; fluctuation of head-to-screen</td>
<td>Distance to the screen; future response accuracy; eye movements</td>
<td>Concurrent high cognitive load leads to movement towards the screen. Posture task is affected by multimedia task.</td>
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### Applied research

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<tr>
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<tbody>
<tr>
<td>Zhao, Gaschler, Kneschke et al., 2020 / 1 Exp.</td>
<td>Multitasking on the screen: future response accuracy, eye movements</td>
<td>Multimedia learning; postural control</td>
<td>Reading condition (question after vs. before material); 5 quintiles of reading; head-to-screen; fluctuation of head-to-screen</td>
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<tr>
<td>13. Zhao et al., 2022 / 1 Exp.</td>
<td>Do students from different grades differ in the ability of text–picture integration?</td>
<td>Multimedia learning</td>
<td>Grade (5 vs. 8); reading condition (question after vs. before material); correct vs. incorrect answers</td>
<td>Completion time; response accuracy; survival rate; fixation patterns on texts and pictures</td>
<td>Individuals from the lower grade tend to give up early, this is mainly due to the inappropriate use of texts and pictures. Demanding students to extract and integrate information from texts and pictures can lead to processing patterns indicating overload.</td>
</tr>
<tr>
<td>14. Zhao, 2021 / 1 Exp.</td>
<td>Does interviewer presence affect learning outcome?</td>
<td>Multimedia learning</td>
<td>Two topics; with vs. without interviewer</td>
<td>Response accuracy</td>
<td>Absence of interviewer leads to better learning outcome. Interviewer presence might constitute multitasking and reduce processing of the content.</td>
</tr>
<tr>
<td>15. Zhao &amp; Gaschler, 2021 / 3 Exp.</td>
<td>Are graph schemas based on perceptual features or common invariant structures in bar, dot, and tally?</td>
<td>Mixing-costs paradigm</td>
<td>Trial type (pure vs. switch vs. non-switch); graph type; position difference of graphs of interests</td>
<td>RT; error rate</td>
<td>Graph schemas are based on common invariant structures. A technique from basic task-switching research (mixing-costs paradigm) can be adopted to study representations of data graphs.</td>
</tr>
<tr>
<td>16. Zhao &amp; Gaschler, 2022 / 3 Exp.</td>
<td>Are graph schemas based on perceptual features or common invariant structures in bar, line, and pie?</td>
<td>Switching paradigm</td>
<td>Trial type (switch vs. non-switch); graph type; position difference of graphs of interests</td>
<td>RT; error rate</td>
<td>Graph schemas might have a hierarchical structure of general schemas and graph-specific schemas. A technique from basic task-switching research (switching paradigm) can be adopted to study representations of data graphs.</td>
</tr>
<tr>
<td>17. Zhao et al. 2023 / 4 Exp.</td>
<td>Does interactive simulation support learning statistics?</td>
<td>Multimedia learning</td>
<td>Interactivity (interactive vs. static); concept (Cohen’s $d$ vs. standard normal distribution)</td>
<td>RT; response accuracy; frequency of interaction</td>
<td>The superiority of interactive pictures cannot be generally assumed. Multiple or single interactive representations might induce multitasking and increase processing time.</td>
</tr>
</tbody>
</table>

Note. SRTT refers to the serial reaction time task. SOA refers to stimulus onset asynchrony. RT refers to response time. Exp. refers to experiments.
2. Multitasking in basic research

Predictable sequences are ubiquitous in multitasking. Yet most studies do not take sequential regularities in multitasking into account (e.g., Pashler, 1994; Ruiz Fernández et al., 2011). Accordingly, Articles 1 to 10 examined whether and how sequential representations can be acquired and used under multitasking.

2.1. Predicting mind by cueing and serial order

Articles 1 to 3 mainly focused on use of cueing and sequence knowledge of serial order as prediction sources in multitasking. Article 1 (Broeker et al., 2017) reviewed the current literature on prediction in multitasking. Predictions about upcoming stimuli and responses can lead to preparation in advance. The preparation can help avoid dual-task bottlenecks (i.e., performance slows down while performing two concurrent tasks, e.g., Luria & Meiran, 2003) and reduce crosstalk (i.e., interference caused by content-dependent codes, e.g., Koch, 2009) by minimizing simultaneous processing of the overlapping information. In a review by the research cluster DFG SPP 1772 Multitasking Article 1 (Broeker et al., 2017), we found that research has scarcely targeted how prediction can support multitasking. We suggested that future multitasking research requires experimental designs and analyses with regard to prediction in multitasking.

Article 2 (Gaschler et al., 2018) compared the use of sequential representations generated by cueing (e.g., knowing the order of four target positions, three have already appeared and only one position can be left) and serial order (e.g., the order of four target positions). So far, cueing and sequence knowledge have been considered separately as sources of prediction. We therefore tested whether both bases for prediction can be acquired and used in multitasking. In this study, participants first practiced SRTT in single tasking. Then they completed trials with an additional visual-manual task with either a random (Experiment 1: \(N = 26\)) or a partially predictable stimulus sequence (Experiment 2: \(N = 33\)). Finally, they performed a single-task block. The sources for prediction in the SRTT were cueing (erasing the placeholders) and sequence knowledge (four positions occurring in a specific order that are practiced by participants). The results showed both cueing and sequence-based prediction could be used in dual-tasking. Dual-task performance did not impede usage of sequence knowledge when a task with a predictable sequence of stimuli was added to the SRTT.
2. Multitasking in basic research

The use of sequence knowledge was only impaired, when a task with random stimulus sequence was added to the SRTT.

Article 3 (Zhao et al., 2018) examined whether two forms of representations of serial orders (i.e., chaining vs. ordinal position) influence speeded typing under multitasking. Chaining refers to associations between subsequent letters, such as w-o-r-d in word (Ebbinghaus, 1885). Ordinal position refers to associations between a letter and its position, e.g., d is in fourth position in word (Henson, 1998). Speeded typing was adopted as a simple sequential task, as it requires people to activate representations of serial orders (Houghton & Hartley, 1996). We varied triplets overlapping between the last word and the current word (no vs. chaining vs. chaining and ordinal position vs. full overlap) under single-task and dual-task conditions, as it allowed to differentiate between different possible variants of representation of serial order. A speeded typing task was paired with a tone counting or a tone identification task in 3 experiments (Experiment 1: \(N = 26\); Experiment 2: \(N = 20\); Experiment 3: \(N = 30\)). The results showed that chaining (association of subsequent letters) and ordinal position (association of item and its position) as representations of serial order influenced speeded typing. Partial overlap of the last word and the current word led to longer RTs than no overlap or full overlap in single-tasking and multitasking. It suggested that the partial activation of representations of serial order has side effects beyond the production of the current sequence. The impact of the secondary task was weak. Importantly, knowledge of serial orders is stored and executed in chunks, as the first keystroke needed much longer time (around 1000 ms) than the inter-keystrokes (around 200 ms). In short, Articles 1 to 3 indicate the predictive mechanism of the human cognitive system.

2.2. Predicting mind by timing

Articles 4 to 5 mainly focused on the use of representations of timing and the roles of timing in performing tasks. Article 4 (Zhao et al., 2019) was a cooperative project with colleagues from the University of Freiburg (funded by DFG 1772 Excellence Grant). It examined whether and how the sequence of stimuli and responses and the sequence of stimulus onset asynchrony (SOA) can be learned and used in multitasking. Timing and upcoming events are often predictable in everyday life (Bausenhart et al., 2006; Marcus et al., 2006; Shin, 2008). Tasks (such as playing piano) contain sequential regularities in time, stimuli and actions that are learned and used to sustain performance. The knowledge about what to respond to (e.g., Koch, 2007) and when to
2.3. The integrative mind

respond (e.g., Thomaschke & Dreisbach, 2013) has often been shown to facilitate the performance on reaction time tasks in single tasking. However, it is not clear how the stimulus and timing sequences can be learned and used in multitasking. In this study, a two-choice task with stimuli and responses in random order was followed by a four-choice SRTT. The four-choice SRTT followed a variable SOA (stimulus onset asynchrony) of either 200 ms or 500 ms. In the sequence blocks, the SOA followed a sequence length of four: 200 ms–200 ms–500 ms–500 ms or 200 ms–500 ms–200 ms–500 ms. The results in two experiments (Experiment 1: $N = 28$; Experiment 2: $N = 30$) yielded that both stimulus and timing sequences can be learned. They contribute independently to dual-task performance—breaking one does not impede the positive effect of the other.

Time-based expectancy is often formed, when a pre-target interval can predict the target with a high probability (Wagener & Hoffmann, 2010). Previous research on time-based expectancy often focuses on binary intervals (short vs. long, e.g., Aufschnaiter et al., 2018; Thomaschke, Kiesel, et al., 2011; Thomaschke, Wagener, et al., 2011) instead of three intervals (short vs. medium vs. long). We thus performed a study by collaborating with colleagues from the University of Freiburg to investigate whether humans can associate three events to three different predictive pre-target intervals (Article 5: Aufschnaiter et al., 2021, funded by DFG 1772 Excellence Grant). The medium intervals varied by their arithmetic mean (Experiment 1: $N = 36$), geometric mean (Experiment 2: $N = 36$) or in between both (Experiment 3: $N = 36$). We found that participants could learn the associations of three events to three intervals. Importantly, participants were able to redirect their time-based expectancy twice in one trial. When participants expected a stimulus to appear at the short interval, and no stimulus was presented after a short interval, they expected the stimulus to be associated with the medium interval. When the stimulus was still not presented after a medium interval, expectancy changed once again with the long interval. It suggested that different timing representations could be active in the same task context. Consistent with previous studies (e.g., Howes et al., 2009; Reuss et al., 2014), Articles 4 to 5 indicate the highly flexible adaptation processes of human cognition.

2.3. The integrative mind

Articles 6 to 8 mainly tested why adding a task with a random stimulus and response sequence to a SRTT task hinders sequence learning (e.g., Rowland & Shanks, 2006; Schmidtke & Heuer, 1997; Schumacher & Schwarb, 2009). Article 6 (Röttger et al.,...
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2019) paired a visual-manual SRTT with different auditory-vocal tone-discrimination tasks in 4 experiments (Experiment 1: $N = 75$; Experiment 2: $N = 50$; Experiment 3: $N = 50$; Experiment 4: $N = 25$). The results suggested that the detrimental effect of dual-tasking on sequence learning is not due to an information-processing bottleneck, as suggested by Schumacher and Schwarb (2009). Rather, participants automatically integrate concurrent elements (i.e., stimuli and responses) of the sequence learning task and the second task with a random stimulus order in joint episodes. As these compound events are partially random, the extraction of the sequential order is hampered.

Article 7 (Röttger et al., 2021) was a follow-up study, which aimed to further explain why sequence learning is impaired in multitasking. An 8-element visual-manual SRTT was paired with an auditory-vocal task. We varied the probabilistic SRTT–tone pairings in three experiments. Experiment 1 ($N = 25$) paired half of the 8 elements in the SRTT to 100% with a specific tone and the other half randomly with one or the other tone. Sequence learning only occurred in the fixed paired elements. Experiment 2 ($N = 25$) paired each of the elements in SRTT with tone identity in a 75%-25% ratio. Sequence learning did not occur. Experiment 3 ($N = 25$) paired each target location in SRTT with a particular tone in 75%-25% ratio. Sequence learning occurred. In short, the results suggested that dual-task interference is mainly due to integrating two separate tasks in one single task set.

While the detrimental effect of dual-tasking on use and acquisition of sequence knowledge has been attributed to task integration of regularly and randomly sequenced events (Articles 6 and 7), direct evidence for across-task integration has been scarce. We therefore conducted a study to examine the existence of across-task integration. In Article 8 (Zhao et al., 2020), participants performed a SRTT with an additional two-choice task with a random stimulus and response sequence in two experiments (Experiment 1: $N = 30$; Experiment 2: $N = 26$). We found that RTs in the current trial were modulated by whether four trials ago (same position in the SRTT) there was by chance the same vs. a different stimulus in the two-choice task. It suggested that sequence learning deteriorates, as the stimuli and responses of the sequence learning task are stored and retrieved as episodes along with the randomly sequenced stimuli and responses of the other task. Taken together, Articles 6 to 8 reveal that the cognitive system automatically integrates and the retrieves the stimuli and responses from two tasks as a joint episode (cf. O'Reilly & Rudy, 2001).
2.4. New indicators for sequence learning

Many studies in multitasking use RT as the main measure to indicate sequence learning (e.g., Curran & Keele, 1993; Frensch & Miner, 1994; Jiménez & Méndez, 2013; Nissen & Bullemer, 1987). However, RT indicates only how quickly the key is hit, but not where and how it is hit. Previous studies (Ewolds et al., 2017; Panzer et al., 2009) have suggested that sequence knowledge allows participants to reduce pauses and overshoots in continuous movement tasks. Article 9 (Gaschler et al., 2019) thus used touch-screen data in three experiments to scrutinize whether response location variability can be influenced by breaking a sequence of target locations under multitasking (Experiment 1: $N = 37$; Experiment 2: $N = 23$; Experiment 3: $N = 26$). We found a dissociation between RT and response location variability. Breaking the sequence led to a larger RT in single-tasking than in dual-tasking, whereas breaking the sequence only led to an increase in response location variability under multitasking. This suggested that response location variability is a promising measure for sequence learning under multitasking.

Sequence learning is often measured by a keyboard, which provides only the time point of the button-press. Yet it has been scarcely studied by using muscle activities (Allain et al., 2004; Burle et al., 2002). Article 10 (Leh et al., 2022) was a collaboration with the University of Giessen (funded by DFG 1772 Excellence Grant). It examined whether sequence learning under multitasking can be measured by muscle activations via electromyography (EMG). One group of participants was informed about the fixed sequence and the other group not. Three dependent variables were assessed: Premotor time is the duration between stimulus onset and the onset of EMG activity, which indicates the start of the response. The EMG integral and tensor decomposition were analysed to assess sequence dependent changes. The EMG integral detects electrical activity of muscles, which can fractionate response times into premotor time and motor time (e.g., Allain et al., 2004). It provides information about the certainty of a reaction and allows detection of response corrections. A tensor is a multidimensional array, and tensor decomposition is a generalized version of matrix decomposition (Kolda & Bader, 2009). It allows to extract spatial modules, temporal modules, and the quantification of changes in the recruitment of these modules (Takiyama et al., 2020). The results yielded that only the explicit group acquired the sequence under multitasking. They had shorter premotor times, larger EMG integral and tensor contributions in fixed sequence blocks than random sequence blocks. This study showed that muscle activity can be a useful indicator for sequence learn-
2. Multitasking in basic research

...ing, which can answer questions beyond RT. Articles 9 to 10 indicate new indicators to measure sequence learning under multitasking.

In summary, Articles 1 to 10 tested whether and how sequential representations can be acquired and used under multitasking. Article 1 exposed a research gap on prediction in multitasking. Articles 2-5 showed that predictive sources (e.g., sequence knowledge of stimuli and responses, timing) can be used in multitasking. Articles 6-8 unraveled the long documented detrimental effect of dual-tasking on sequence learning and demonstrated that this can be due to to the automatic encoding processes and the retrieval of joint task episodes. It is consistent with Ewolds et al. (2020), which used the auditory go/no go reaction time task and propose a phenomenon of task integration in multitasking. Articles 9-10 used movement tasks and suggested that sequence knowledge can be indicated by the spatial variability on screen and muscle activities. This series of experiments in basic research exemplify that the mind uses representations (e.g., serial orders, timing, movements) to predict the upcoming stimulus and response. The mind tends to automatically encode and retrieve the stimuli and responses of the two tasks as one.
3. Multitasking in applied multimedia learning scenarios

Previous studies on modality in multitasking (Broeker et al., 2021; Doherty & Logie, 2016; Langhanns & Müller, 2018; McLeod, 1977; Treisman & Davies, 2012; Wickens et al., 1984) suggest that two parallel tasks only interfere with each other when they share the same mental resource. Therefore, multitasking can be used as a window into the mind by examining which type of resources are required in processing the task based on dual-task interference. The link between two tasks which share mental resources can be used to assess the cognitive state during multimedia learning. Multimedia learning refers to learning from texts as well as pictures, which is one of the most ubiquitous learning scenarios (cf. Mayer, 2014; Paivio, 1986; Schnottz & Bannert, 2003). Previous studies (Gyselinck et al., 2002; Gyselinck et al., 2000; Kruley et al., 1994) showed that the visuospatial sketchpad is involved in the integration of texts and pictures. Processing information involving the visuospatial sketchpad can interfere with these tasks that also involve the visuospatial sketchpad, such as Origami folding (Taylor & Tenbrink, 2013), or postural control (Igarashi et al., 2016; Kerr et al., 1985). Accordingly, from a multitasking perspective Articles 11 to 17 examined whether and how texts and pictures can be acquired and used in applied learning scenarios.

3.1. Taxing mental resources using multitasking

Article 11 (Zhao et al., 2020) examined which types of memory load are involved in the acquisition and execution of Origami folding. Dual-task interference is assumed to occur, if Origami folding requires the same mental resource as the memory load (for a review, see Strobach et al., 2018; Wickens, 2008). Fifty-three participants repeatedly folded 5 Origami figures (a type of sequential skill) in four runs while performing secondary memory-load tasks (i.e., verbal load, spatial load, isochronous timing load, non-isochronous timing load, and none). According to Willingham (1998), learning stems from motor control processes (i.e., selecting, sequencing, and transforming targets into muscle commands). In line with his perspective, we did not observe cases where a dual-task variant influenced performance while it did not affect learning. Visuospatial memory load and isochronous timing load interfered with the acquisition of Origami folding skill, suggesting the use of a visuospatial sketchpad and an absolute timing mechanism when learning Origami folding.
3. Multitasking in applied multimedia learning scenarios

Previous research has provided a link between postural control and cognitive processing (Bonnet et al., 2017; Cocchini et al., 2004; Kaakinen et al., 2018; Woolacott & VanderVelde, 2008). According to the multiple resource theory (Wickens, 2002), when a cognitive task demands large amount of attention, less attention can be allocated to postural control, which can lead to degraded performance in postural control. Article 12 (Zhao et al., 2020) examined the flexible allocation of attention between a cognitive task and a postural task. 144 children ($M_{age} = 13$ years, $SD = 3.2$) were told to maintain a fixed sitting posture while reading and answering questions at three difficulty levels (i.e., easy vs. medium vs. difficult). The distance to screen was recorded by an eye-tracker. Results yielded that task difficulty influences how well the distance to the screen can be regulated. Closer head-to-screen distance and larger fluctuation of head-to-screen distance can reflect that participants are engaging in a challenging task. This study suggested that the link between distance to screen and the processing of a cognitive task can be used to unobtrusively assess reader’s cognitive states during system usage.

A further analysis (Article 13, Zhao et al., 2022) revealed that the grade students are in can be related to their ability to integrate text and pictures. Students in the lower grade ($5^{th}$ graders compared with $8^{th}$ graders) tended to give up early when they encountered difficulties in multimedia learning. This premature termination can be due to the inappropriate usage of texts and pictures. It provides a basis for automated feedback during multimedia learning, especially for younger students who give answers quickly and whose recorded use of texts and pictures is inappropriate. This suggests that demanding students to extract and integrate information from texts combined with pictures can lead to processing patterns that indicate overload.

Interviews with scholars are often used as e-learning materials. Yet how an interview video should be edited is mostly based on personal preference rather than on rigorous scientific research. In Article 14 (Zhao, 2021), the author interviewed two psychology professors and edited the videos in either with-interviewer or without-interviewer versions. When the interviewer is shown together with the interviewee, it can be considered as a multitasking condition where learners have to divide their attention on both people’s languages and body movements. In without-interviewer videos, the questions raised by the interviewer were displayed by words on slides. 180 psychology students watched the videos and answered the corresponding questions. Results yielded that the without-interviewer videos led to superior performance compared with the with-interviewer videos. It is possible that the absence of the interviewer protects learners from splitting their attention on two subjects. In line with
previous studies (Ayres & Sweller, 2005; Pouw et al., 2019), segmenting the interview videos by using keywords on slides fosters essential processing by displaying information in textual and pictorial forms. Articles 11-14 imply that multitasking can be used to tax working memory indicating which mental resources are involved in processing the task. The deterioration of learning performance under multitasking can be used to guide the design of multimedia learning materials.

3.2. Graph schema by using a technique from task switching

Techniques originally developed in basic multitasking research can be utilized to study information processing in applied settings. Articles 15-16 adopted the mixing-costs paradigm from task switching (Kiesel et al., 2010; Monsell, 2003) to study whether graphs are processed based on general vs. specific graph schemas. The mixing-costs paradigm has been used as a method to isolate the process of activating a graph schema by pairing graphs in pure and mixed blocks (Ratwani & Trafton, 2008). It allows the determination of whether two graphs are processed by the same or different schemas. If a pair of graphs are processed by distinct schemas, it should take longer to load the appropriate schema than if they use the same schema. Therefore, two graphs utilizing different schemas should result in longer RTs in mixed blocks than in pure blocks, as the appropriate graph schemas must be activated. Rather than merely assessing which data graph seems to be the most efficient for which purpose, the mixing-costs paradigm can reveal the processes people use to extract information from a data graph. Knowledge of these processes facilitates our understanding of how external representations are used and informs design decisions in data visualization.

Article 15 (Zhao & Gaschler, 2021, Experiment 1: \(N = 39\); Experiment 2: \(N = 19\); Experiment 3: \(N = 40\)) examined graph schemas of horizontal bar graph vs. dot plot vs. tally chart. The results suggested that the human cognitive system might contain several common invariant graph schemas, which can guide people in decoding visual representations to conceptual information and insert new information into a complex knowledge representation (Pinker, 1990; Simkin & Hastie, 1987). Article 16 (Zhao & Gaschler, 2022, Experiment 1: \(N = 60\); Experiment 2: \(N = 41\); Experiment 3: \(N = 58\)) tested graph schemas of vertical bar graph vs. line graph vs. pie chart. It suggested that pairing graphs that differ in general and graph-specific schemas can lead to more switch costs than pairing graphs that differ only in graph-specific schemas. Consistent with Pinker (1990), Articles 15-16 suggest that graph comprehension can be based on a hierarchical structure of common invariant graph schemas and underlying specific
3. Multitasking in applied multimedia learning scenarios

3.3. Exploration and exploitation with interactive data graphs

Basic laboratory work on multitasking has recently begun to take multitasking situations into account in which people choose between different courses of action (Brüning & Manzey, 2018) rather than being provided with stimuli that demand specific responses on the spot. Yet so far multitasking studies have been restricted to setups where participants are presented with stimuli, from which they are to directly choose. In online learning environments and many other setups, participants are required to process on-screen information and also explore new information in simulations (cf. exploitation-exploitation dilemma, Marković et al., 2019). Past work has underlined the power of active manipulation in basic learning setups (Blaisdell, 2008; Buckmann et al., 2015; Gaschler et al., 2012). Article 17 (Zhao et al., 2023) thus examined how learning is influenced by allowing for multitasking combining interactively manipulating data graphs while reading from them. In four experiments (Pilot study: \( N = 26 \); Experiment 1: \( N = 152 \); Experiment 2: \( N = 117 \); Experiment 4: \( N = 119 \)), participants were asked to learn two statistical concepts accompanied either with interactive simulations or static pictures. Although human learning can profit from repeated interaction under user control (e.g., de Jong & van Joolingen, 1998; Domagk et al., 2010; Fawcett, 2018; Iten et al., 2014), this study suggested that interactive simulations impose high demands on learners. Learners had to divide their attention while reading information from the screen and exploring new information, which indicates multitasking. There was a learning bias: Interactive simulation was not advantageous in learning outcomes but was preferred. This study suggested that, due to multitasking, one cannot generally assume that adding the opportunity of exploration can lead to better learning.

In summary, Articles 11 to 17 advance our understanding on the interplay of representations and the processes operating upon them from a multitasking perspective in applied learning scenarios. Articles 11-14 showed that multitasking can be used to detect the resources demanded in processing the task. Articles 15-16 employed a technique from task switching in basic multitasking research to study graph comprehension. It suggested that graphs can be processed based on a hierarchical structure with several common invariant schemas and specific graph schemas. In Article 17, multitasking was present in form of regulating the active exploration of tools in online learning environments while consuming the available information.
4. Discussion

Given the fact that the mind cannot be directly inspected, this thesis (including 17 articles) uses multitasking as a window into the mind to examine the interplay of representations and the processes operating on these representations in basic laboratory studies as well as in applied learning scenarios. Multitasking studies in basic research (Articles 1-10) underline that the cognitive system has the mechanism to form predictions. Multitasking studies in applied research (Articles 11-17) suggest that the resource metaphor from multitasking can be useful when employing a multitasking perspective to address research questions in multimedia learning. In this thesis, we often compared the performance of single tasking and multitasking (Articles 2-3, 6-7, 9, 11). Additionally, we observed a training effect with participants performing slower in the first few blocks than the later blocks (Articles 2-4, 6-11, 15-16). It opens up the discussion on what the advantages of multitasking as a window into the mind are compared to alternative approaches, such as single tasking and cognitive training research.

4.1. Single tasking vs. multitasking

Compared with single-tasking interference paradigms, multitasking paradigms might be more suitable to inspect the response—selection processes of the cognitive system. In single-tasking interference paradigms (e.g., Stroop, Flanker\(^1\) and Simon tasks\(^2\)) participants perform a task with irrelevant information, which causes interference to affect task processing (cf. for a review, see MacLeod, 1991). Congruent trials (e.g., the word *red* is in red ink in a Stroop task, Stroop, 1935, 1992) are typically responded to faster and more accurately than incongruent trials (e.g., the word *red* is in grey ink). Two main corollary assumptions are proposed. One presumes that the single bottleneck allows serial processing of relevant and irrelevant responses—only one response can be executed at a time, and the order of execution depends on the speed of

\(^1\) In a Flanker task (Eriksen & Eriksen, 1974), irrelevant shapes, letters or words (flanker stimuli) are presented surround the target. For instance, H and K letters are associated with the right button, and S and C letters are associated with the left button. HHHKHHH is a congruent trial because both letters are associated with the right direction. HHHSHHH is an incongruent trial because the target letter and the surround letters are associated with different directions.

\(^2\) In a Simon task, irrelevant spatial information is presented together in a visual choice-reaction task (for overviews see Lu & Proctor, 1995; Simon, 1990). The right button is associated with a red stimulus on the screen, and left button with a green stimulus. If the red stimulus appears on the right side of the screen, it is a congruent trial. If the red stimulus appears on the left side, it is an incongruent trial. The opposite is true for the green stimulus.
processing (Dyer & Severance, 1973; Posner & Snyder, 1975; Stroop, 1935). The other assumption assumes that the single bottleneck allows parallel processing of relevant and irrelevant responses—evidence is accumulated until a threshold is exceeded (Logan, 1980) or the interconnected pathways are selected or strengthened (Cohen, 1990).

In contrast, in multitasking paradigms (e.g., dual-task vs. single-task, psychological refractory period, task switching, for a review, see Koch et al., 2018), participants experience interference among the information from two tasks while both tasks are relevant. Multitasking research focuses on the emergence of dual-task interference when the cognitive system divides its attention between different stimulus-response processes. It can provide hints on what the bottleneck looks like and how different relevant information is processed with limited processing capacity.

The structural bottleneck model and capacity sharing model are proposed based on the findings of dual-task interference. The **structural bottleneck model** (Pashler, 1984) refers to three sequential processing stages: perception, response selection (central stage), and response execution. It is presumed that the stage of response selection has severely limited capacity, in which only one task can be processed at a time (a central bottleneck, Pashler, 1994). Dual-task interference occurs because the stage of response selection in the bottleneck model is processed sequentially. Task 2 is postponed until the response selection stage in Task 1 is completed. **Capacity sharing** refers to increased dual-task interference, when two tasks are similar in task-specific processing codes (e.g., Allport et al., 1972). Capacity sharing assumes that the bottleneck consists of separate modality-specific and code-specific resources instead of a generic processing capacity (Wickens, 2002; Wickens et al., 1984). This view has been supported by the findings that the dual-task costs are smaller in visual-manual modality mappings than in visual-vocal mappings, as visual-vocal mappings are more strongly associated than the visual-manual mappings (e.g., Hazeltine et al., 2006). This thesis also provides evidence for capacity sharing, as dual-task interference can occur when the same mental resources are required in the primary and secondary tasks (e.g., Articles 11-12). Compared with the single bottleneck view generated by single-tasking interference paradigms, the perspectives of central bottleneck and capacity sharing derived from multitasking paradigms provide more detailed information about the processes operating upon representations. Therefore, multitasking is more suitable than single-tasking interference paradigms to unravel the response-selection processes of the cognitive system.

Several research questions and setups in this thesis should additionally be addressed by using a single-tasking interference paradigm rather than multitasking.
For instance, in Article 8 (Zhao et al., 2020), we focused on the across-task integration. One can use a single-tasking interference paradigm to test whether tasks are stored and retrieved together with irrelevant information. In Articles 9-10 (Gaschler et al., 2019; Leh et al., 2022) one can use a single-tasking interference paradigm to test whether measures of spatial variability and muscle activities can be affected by irrelevant interference.

4.2. Cognitive training research vs. multitasking

Compared with cognitive training research, multitasking research might be more suitable to examine the plasticity of the cognitive system. The main focus of cognitive training research is to investigate whether practice can significantly enhance capacities of human perception and cognition (James, 1890; Woodworth & Thorndike, 1901). It is suggested that these capacities can be improved and permanent cognitive as well as neural changes in the brain can occur after extensive training (for a review, see Belleville & Bherer, 2012; Klingberg, 2010; Sala et al., 2018; Schmidt & Bjork, 1992; Schmiedek et al., 2014). Training-related transfer takes place only when training is process-based and the process of the trained task and the transfer task overlap (Dahlin et al., 2008; Taatgen, 2013). In strategy-based training, improvements occur on task-specific procedures and strategies, and only the trained task will be improved, thus no transfer effect can be found (e.g., Baltes & Kliegl, 1992; Kliegl et al., 1990). Moreover, age-related differences have been considered for the transfer effects in testing-the-limits approach (cf. Lindenberger & Baltes, 1995). For instance, younger adults began at a higher level and improved quicker through practice compared to the older adults in a ten-day training on working memory (Bürki et al., 2014) or over a year training on the method of Loci (i.e., a method to use mental imagination to encode and recall word lists, Baltes & Kliegl, 1992). This supports the assumption of an age-related decline in the upper limits of plasticity (i.e., performance potential).

Recent research has suggested that multitasking performance can also be significantly optimized and dual-task costs can be significantly eliminated with extensive practice (Hazeltine & Teague, 2002; Liepelt, Fischer, et al., 2011; Liepelt, Strobach, et al., 2011; Schubert et al., 2017; Schubert & Strobach, 2018; Spelke et al., 1976; Strobach et al., 2012). For instance, Schumacher et al. (2001) showed that the dual-task costs were reduced after two joint tasks (visual-manual vs. auditory-verbal) have been trained one hour a day over five days. This thesis also provides evidence for the training effect under multitasking (e.g., Article 11, Zhao et al., 2020). The reduced
4. Discussion
dual-task costs can be explained in two perspectives. On the one hand, the processing stages can be shortened after extensive practice, and the shortened stages eliminate the overlap of the response selection stages, resulting in reduced delay of the second task (Ruthruff et al., 2003). On the other hand, the cognitive system is more able to parallelly select responses for multiple actions after practice (cf. strategic postponement view, Lien et al., 2007; Meyer & Kieras, 1997a, 1997b).

Training-related transfer effects have also been documented in multitasking studies (e.g., Liepelt, Strobach, et al., 2011; Schubert et al., 2017; Schubert & Strobach, 2018). It is shown that performance in a novel dual-task situation (i.e., different stimulus and response mapping compare to the trained tasks) can be improved after extended dual-task training (e.g., alternatively showing Task 1 and Task 2) instead of single-task training (e.g., separately showing Task 1 and Task 2). Coordination skill—an ability to load information of the task quickly and efficiently in working memory—is claimed to be acquired during the dual-task training. It can accelerate the switching operation between two tasks in the response selection stage (Strobach et al., 2014). The coordination skill is not fully task-specific, as it can be transferred to novel dual-task situations (Liepelt, Strobach, et al., 2011). Compared with cognitive training research, multitasking provides more explanations about the optimization of performance with practice, such as shortened processing stages, parallel response selection stages, and coordination skills. Taken together, research on dual-task practice is more suitable than cognitive training research to test the plasticity of the cognitive system.

The research question and setup in Article 11 (Zhao et al., 2020) should additionally be addressed by using a paradigm in cognitive training rather than multitasking. In this study we focused on the shared mental resources of memory loads and Origami folding. One can use the paradigm in cognitive training to study the acquisition stages of a sequential skill (cf. Karni et al., 1998; Weaver, 2015). According to previous studies (Dahms et al., 2020; Fitts & Posner, 1967; for a review, see Seidler et al., 2012; Willingham, 1998), the sequential order of movement is acquired with rapid improvement in the early learning stage, and performance of the task is cognitively demanding. In the late learning stage, there are slow performance gains over hours or days of practice, and execution of the task is more automatic.
4.3. Future studies

This thesis raises new questions and extends the knowledge border of how the mind works by using multitasking as a window. Further study should examine how representations of hierarchical serial orders (e.g., Origami folding including many sub-goals and a general goal) are acquired with practice under multitasking. The underlying mechanism of practice is that several elements of the sequence are integrated into chunks, and the chunks are dealt with as one or more representations after practice (G. A. Miller, 1956). As chunks are combined representations of elements, the storage capacity and retrieval capacity can break the restriction of seven plus and minus two elements (Gallistel, 1980). For instance, Article 3 (Zhao et al., 2018) revealed the evidence of chunking in speeded typing. For the first keystroke, participants needed in average around 1000 ms, but for the inter-keystrokes only 200 ms. Typing is a relatively automated action, as we have been trained for years in schools to read and write. However, it is not yet clear how a relatively untrained sequential skill like Origami folding is acquired with practice. Further study should therefore examine whether the performance of the first step differs from the performance of inter-steps in Origami folding, and whether the difference between the first step and the inter-steps decreases with practice. Multitasking can be used to test which types of resources are involved in acquisition and execution of the first step and the inter-steps.

Moreover, interactive illustrations are not beneficial for all learning tasks and are shown to be beneficial for learners with relatively low prior knowledge or cognitive abilities on the subject matter (Rasch & Schnotz, 2009). It is therefore of great interest to investigate how, whether, why and to what extent systematically exploring interactive graphs while processing information facilitate knowledge acquisition. Future studies should also focus on how to enhance exploration in interactive learning by using decorative pictures (Duesbery et al., 2011; Lenzner et al., 2013; Schneider et al., 2018), since interaction is not spontaneous (Article 17: Zhao et al., 2023). Furthermore, previous eye-tracking studies (Lindner et al., 2017; Zhao et al., 2020) have shown that readers are more likely to shortly fixate pictures at the beginning of reading (i.e., scaffolding function of pictures) and intensively focus on pictures at the end of reading (i.e., decision-making function). However, it is not yet clear whether there is a sequential constraint in interactive learning, and whether learners with high vs. low learning outcomes differentiate from each other regarding interactive patterns (Liaw & Huang, 2013). In addition, the exploration–exploitation dilemma should be tested in an authentic learning environment like Moodle, as there is not enough empirical
4. Discussion

evidence on whether to provide all the materials at once to the learners or to allow access to one unit after the previous unit is accomplished.

4.4. Educational implications

This thesis provides educational implications. For instance, it suggests considering distance to screen as a variable in personalized learning systems. As postural seems to interfere with cognitive processing, deteriorated postural control (e.g., closer head-to-screen and more fluctuation of head-to-screen) can indicate a high cognitive load (Article 12: Zhao et al., 2020). Therefore, tracking distance to screen can be used to monitor the cognitive state of learners while they interact with electronic devices. When the head-to-screen distance decreases and the fluctuation increases, the computerized learning system can detect the high cognitive load and can provide adaptive assistance. This support can be especially useful for younger students (5th graders compared with 8th graders), as they tend to give up early if they have a challenging task (Article 13: Zhao et al., 2022).

This thesis uses multi-faceted multimedia materials to examine how we use and learn from the representations of texts and pictures, such as static text–picture blended material, interview video, data graphs, and interactive simulation. Article 13 (Zhao et al, 2022) provided a contribution on the relationship of the grade and the ability to integrate text and pictures. Article 14 (Zhao, 2021) indicated how to edit interview videos and fills the gap on interview learning (Brame, 2016; Choe et al., 2019; Fiorella & Mayer, 2018). Articles 15-16 (Zhao & Gaschler, 2021; 2022) used a task-switching paradigm and suggested we probably extract information in graphs by using several general graph schemas and graph-specific schemas. A general graph schema is a generic scaffold that guides readers in inserting new information into a complex knowledge representation (Pinker, 1990). A graph-specific schema includes the unique features of individual graphs, such as bars with different heights or widths. Article 17 (Zhao et al., 2023) suggested that instructors should not generally assume that interactive learning leads to a better learning outcome. Exploration in interactive learning can lead to a longer study time but similar response accuracy than in static learning. Instructors should not use multiple interactive simulations. Nevertheless, interactive learning is preferred over static learning.

The Covid-19 pandemic strengthens the topic on use and acquisition of representations of multimedia, as most schools and universities are teaching online. This thesis has demonstrated that multitasking can tax cognitive resources. When two
tasks share the same sources, dual-task costs can occur. Thus, instructors should create a learning environment with tasks that have no overlapping features. Importantly, this thesis shows that learning difficulties can be detected not only from errors or RTs, but also from postural status (Article 12: Zhao et al., 2020).

4.5. Conclusion

In conclusion, this habilitation thesis includes 36 experiments targeting the interplay of representations and the processes operating upon them. It suggests that multitasking can be used as a window into the mind. It demonstrates that the human mind is a prediction-driven mechanism to deal with the noisy world (e.g., M. Miller & Clark, 2018). This mechanism actively selects regulations to lower demands on working memory. The mind automatically integrates representations of two tasks to a joint episode and flexibly adapts to the situational demands (e.g., Frings et al., 2020). The mind’s operating processes on representations share multiple resources. The mind processes external representations based on general graph schemas and graph-specific schemas. This thesis extends our knowledge on cognitive structure, flexibility and plasticity of our cognition. The cognitive system has the hierarchical structure to store and retrieve acquired knowledge: Chaining and ordinal positions are processed separately in chunks; Graph schemas are organized in general graph schemas and graph-specific schemas. The cognitive system is highly flexible in altering the associations of time and the specific stimulus. The cognitive system is highly plastic by integrating two tasks into one to alleviate the dual-task interference. This thesis provides important contributions not only in the basic laboratory research but also in ubiquitous learning scenarios with texts and pictures. The studies further provide a working basis for the current project of my junior research group Multimedia at CATALPA (Center of Advanced Technology for Assisted Learning and Predictive Analytics) at FernUniversität in Hagen.
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5. Declaration

Ich erkläre, dass ich die schriftliche Habilitationsleistung selbstständig und ohne unzulässige Inanspruchnahme Dritter verfasst habe. Ich habe dabei nur die angegebenen Quellen und Hilfsmittel verwendet und die aus diesen wörtlich, inhaltlich oder sinngemäß entnommenen Stellen als solche kenntlich gemacht.


Fang Zhao

Hagen
October 2022
6. Publications included

Note: * student co-authors (BSc./MSc. students of FernUniversität contributing via thesis)


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