Determinants and consequences of offloading working memory processes

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Summary

In my PhD-project I investigated the externalization of working memory processes into technical tools (i.e. cognitive offloading). Thereby, two main research questions arose – first, how do individuals decide to offload working memory processes and second, what consequences does this offloading behavior have on immediate and subsequent task performance. Regarding the former, I performed two studies investigating metacognitions as determinants of cognitive offloading. To measure offloading behavior, I used and adapted the Pattern Copy Task – a free choice offloading paradigm. While I did not find a relationship between metacognitive beliefs and offloading behavior in Study 1 ($N = 80$), I used fake performance feedback (below-average vs. above-average vs. no feedback) to experimentally manipulate metacognitive beliefs in Study 2 ($N = 159$). The participants adopted their metacognitive beliefs according to the feedback, but there were no group effects on offloading behavior. I argue that rather actual working memory performance and related metacognitive experiences act as a predictor for cognitive offloading than metacognitive beliefs. Regarding the consequences of offloading behavior, in Study 3 I observed a trade-off between enhanced immediate task processing but decreased subsequent memory performance due to cognitive offloading within three experiments (each $N = 172$). Nonetheless, cognitive offloading was not harmful for long-term memory formation under all circumstances. If participants were forced to offload maximally but also had the intention to foster a strong long-term memory detrimental effects of offloading could be counteracted. In a last study (Study 4, $N = 133$) I tested whether cognitive offloading in one task is beneficial for the performance of a simultaneous secondary task. When participants offloaded more within the Pattern Copy Task due to low temporal costs associated with offloading, they showed a better secondary task performance than when they offloaded less due to high temporal costs. Cognitive offloading might therefore foster secondary task performance; however, this influence is not fully

explained yet. My studies provide a systematic investigation of the omnipresent phenomena "cognitive offloading" and serve for a better understanding of humans' technical tool use.

Zusammenfassung

In meinem Dissertationsprojekt habe ich die Auslagerung von Arbeitsgedächtnisprozessen in moderne, technische Hilfsmittel (sogenanntes *Cognitive Offloading*) untersucht. Dabei stellten sich zwei zentrale Forschungsfragen - erstens, wie entscheiden sich Individuen Arbeitsgedächtnisprozesse auszulagern, und zweitens, welche Auswirkungen hat dieses Offloading-Verhalten auf die unmittelbare und nachfolgende Aufgabenbearbeitung. Im Hinblick auf Ersteres habe ich zwei Studien durchgeführt, in denen Metakognitionen als Determinante für Cognitive Offloading untersucht wurden. Zur Messung des Offloading-Verhaltens verwendete und adaptierte ich den Pattern Copy Task, der einen individuellen Gebrauch von Cognitive Offloading erlaubt. Während ich in Studie 1 ($N = 80$) keinen Zusammenhang zwischen dem metakognitiven Glauben an eigene Gedächtnisfähigkeiten und individuellem Offloading-Verhalten fand, verwendete ich in Studie 2 ($N = 159$) falsches Leistungsfeedback (unterdurchschnittlich vs. überdurchschnittlich vs. kein Feedback), um den metakognitiven Glauben von Versuchspersonen experimentell zu manipulieren. Wie erwartet passten die Versuchspersonen ihren metakognitiven Glauben dem Feedback an, aber es gab keine Effekte auf das Offloading-Verhalten im Pattern Copy Task. Ich argumentiere, dass anstelle des metakognitiven Glaubens die tatsächliche Arbeitsgedächtnisleistung und damit verbundene metakognitive Erfahrungen einen Prädiktor für Cognitive Offloading darstellen. Im Hinblick auf die Folgen von Cognitive Offloading beobachtete ich in Studie 3 einen Trade-off zwischen einer verbesserten unmittelbaren Aufgabenbearbeitung und einer verminderten späteren Gedächtnisleistung aufgrund des Offloading-Verhaltens über drei Experimente hinweg (á $N = 172$). Nichtsdestotrotz war das Auslagern von Arbeitsgedächtnisprozessen nicht unter allen Umständen schädlich für die Bildung von Langzeitgedächtnis-Repräsentationen. Wenn die Versuchspersonen gezwungen wurden ihre Arbeitsgedächtnisprozesse maximal auszulagern, aber

auch die Absicht hatten, ein starkes Langzeitgedächtnis zu bilden, konnten sie den schädlichen Auswirkungen von Cognitive Offloading entgegenwirken. In einer letzten Studie (Studie 4, $N = 133$) habe ich untersucht, ob Cognitive Offloading bei einer Aufgabe vorteilhaft für die gleichzeitige Durchführung einer Zweitaufgabe ist. Wenn die Versuchspersonen innerhalb des Pattern Copy Tasks aufgrund niedriger zeitlicher Kosten, die mit dem Offloading verbunden waren, mehr Arbeitsgedächtnisprozesse ausgelagert haben, zeigten sie eine bessere Leistung bei der Zweitaufgabe als wenn sie aufgrund hoher zeitlicher Kosten weniger ausgelagert haben. Cognitive Offloading scheint daher die Leistung in der Zweitaufgabe zu fördern, allerdings ist dieser Einfluss noch nicht vollständig geklärt. Meine Studien liefern eine systematische Untersuchung des allgegenwärtigen Phänomens "Cognitive Offloading" und dienen einem besseren Verständnis der täglichen Nutzung technischer Hilfsmittel.

1. Introduction

In everyday life, individuals constantly use tools to support their performance in various activities. Tools can not only support physical actions, such as using a lemon squeezer instead of squeezing a lemon by hand, but they can also be used to support cognitive processing such as memory (Osiurak, Navarro, Reynaud, & Thomas, 2018). For instance, one could use a notepad to write down notes instead of memorizing them. Humans have externalized cognitive processes already thousands of years ago (Nestojko, Finley, & Roediger, 2013). While in the past, individuals might have used a simple piece of paper to externalize memorization, these days modern technical tools such as smartphones or tablets can be administered for externalization and thus support cognitive processing. In 2014, only 55% of the German population used smartphones on a regular basis, whereas in 2018 already 81% of Germans used them regularly (Bitkom Research, 2019). Additionally, every sixth German adult owns a tablet device (Bitkom Research, 2020). Hence, there is an increasing distribution of technical tools which simplifies and accelerates the externalization of cognitive processes. In addition to note taking, individuals can also, for example, use a smartphone's calendar function to save appointments instead of memorizing them, or the calculator function instead of doing mental arithmetics, or the navigation app instead of finding a way themselves. Due such externalizations individuals can overcome limitations of internal cognitive processing (Risko & Gilbert, 2016). Effortful cognitive processing such as holding information in memory is externalized into the technical tool at hand and thus individuals do not need to solely rely on their restricted internal cognitive processing.

It is beyond dispute that externalizations of cognitive processes with modern technical tools influence humans' private life, their education, and their work environment. While in humans' everyday life external memory stores when using technical tools play a growing role (Finley, Naaz, & Goh, 2018), technical tools are also widely distributed in educational as well as working contexts (Krull & Duart, 2017; Pimmer, Mateescu, & Gröhbiel, 2016). For instance, in higher education settings (e.g., universities), modern technical tools are administered more and more to support lectures (Krull & Duart, 2017; Pimmer, et al., 2016). Also, regarding children's education in schools, multiple countries are counting on digitalization with technical tools to support teachers in their classes (e.g, see "DigitalPakt Schule" in Germany or "Masterplan Digitalisierung" in Austria). Especially in times of Covid-19 and the accompanying shift to home-schooling, technical tools play an important role for learning. A recent study suggests that 82% of German pupils (12 – 19 years old) use their smartphones for studying during the Coronavirus-pandemic (JIMplus, 2020). Moreover, also in working environments individuals come across technical tools that should help to simplify their tasks. For example, a waitress might be using a tablet device to enter an order instead of using a more effortful externalization process such as writing it down on paper or even not externalizing the order at all (i.e. memorizing the information).

In the present PhD-project I focused on these ubiquitous externalizations of working memory processes into modern technical tools. In the following theoretical overview, I will start with introducing the general concept of externalization (i.e. cognitive offloading) and then specifically focus on the offloading of working memory processes. Thereafter, I will describe two lines of research that are important for the development of the present project. First, I will elaborate on possible determinants of offloading working memory processes and second, I will elaborate on potential short-term and long-term consequences of offloading behavior. At the end of this chapter I will shortly describe my research questions and proposed studies for each of these two lines of research.

1.1 Cognitive Offloading

The externalization of cognitive processes is referred to as *cognitive offloading.* Cognitive offloading describes the use of physical actions to modify the requirements of information processing in order to reduce the cognitive demands of a task (Risko & Gilbert, 2016). Therefore, when offloading cognitive processes physical actions are used to manipulate one's body or one's physical environment. This offloading behavior in turn reduces demands of internal cognitive processing, thus making a task less effortful (Risko & Gilbert, 2016). Over the last years, not only cognitive offloading has been used as a term to describe externalizations of cognitive processes, but research has also used other terms (Risko & Gilbert, 2016). For instance, Kirsh and Maglio (1994) introduced the term *epistemic actions* describing physical actions making mental computation easier, more reliable, and faster. Similarly, Scaife and Rogers (1996) described the use of external representations such as diagrams or animations in order to solve informationally problems as *computational offloading*. In external representations relevant information is offloaded that would otherwise need to be stored in one's memory. The use of external representations should therefore reduce the invested cognitive effort when solving problems and facilitate problem solving. Moreover, Wegner (1987; 1995) introduced the term *transactive memory system* describing the distribution of information among several individuals to support each other's performance. In a transactive memory system other humans can act as transactive memory partners, but also technical tools can be used to externally store information for individuals (e.g., Wegner & Ward, 2013). This creates a *human-technology transactive memory system* that does not require individuals to remember the content of information that is stored in the technical tool but they still need to remember where relevant information is stored (Risko & Gilbert, 2016). With regard to using technical tools to externalize cognitive processes, Salomon (1990; Salomon & Perkins, 2005) introduced two ways how technology shapes humans' cognition. On the one hand, he introduced *effects with technology* describing effects that arise immediately while working with technical tools such as an improved immediate task performance. On the other hand, he described *effects of technology* concerning the cognitive residues that arise after the use of technical tools (e.g., long-term skill acquisition). In the present thesis all these different concepts describing externalizations of cognitive processes will henceforth be summarized as cognitive offloading.

Overall, cognitive offloading can be divided into *offloading onto the body* and *offloading into the world.* When offloading onto the body, individuals use their body to decrease cognitive demands such as using gestures when talking, finger counting to solve an arithmetic task, or tilting one's head to read a tilted text (Risko & Gilbert, 2016). With regard to offloading into the world, individuals' external environment is used to support cognitive processing (Risko & Gilbert, 2016). For instance, post-it notes can be placed as reminders for future tasks or a shopping list can be typed into a smartphone to later access it in the supermarket. Thus, using technical tools for cognitive offloading also falls in this latter category – offloading into the world. Via cognitive offloading technical tools extend individuals' internal cognitive skills (Osiurak, et al., 2018) and can be seen as an extended mind (Clark & Chalmers, 1998). Related to that, technical tools that are used to offload cognitive processes might imply an extended self. This view might arise from the tendency of individuals to heavily rely on technical tools to support cognitive processing (Clark & Chalmers, 1998). Cognitive processes that are offloaded particularly often into technical tools are memory processes. The majority of people questioned in an interview study indicated that they often – if not always – offload memory processes (Finley et al., 2018). In the present PhD-project I especially focused on the offloading of information that would need to be stored in the strictly limited working memory.

1.2 The offloading of working memory processes

Unlike the massive storage capacity of modern technical tools, a human's working memory is strictly limited. Working memory is a cognitive system that enables the temporal storage and manipulation of information that is used for cognitive tasks such as comprehension and learning (Baddeley, 1992; 2003). However, the strict limitations of working memory only allow the storage of a small amount of information for a short time period (Baddeley, 2003; Luck & Vogel, 2013). For instance, the capacity of visual working memory that actively maintains visual information for the task at hand can only hold about three to four visual objects at a time (Baddeley, 2003; Luck & Vogel, 2013). Working memory capacity is often correlated with performance in cognitive tasks; thus, the higher individuals' working memory capacity is, the more successful they are in performing cognitive tasks (Baddeley, 2003; Luck & Vogel, 2013). Therefore, working memory capacity accounts for individual differences in broad cognitive abilities (Luck & Vogel, 2013).

To overcome limitations of working memory and to support performance in working memory tasks, cognitive processing can be externalized into technical tools (Risko & Gilbert, 2016). Due to the offloading of working memory processes into technical tools the nature of a task changes (Zhang & Norman, 1994). Instead of solely relying on internal working memory, individuals make the external environment (e.g., a technical tool) store and manipulate the necessary information for them and they only access the information when needed (Wilson, 2002). Thereby, internal working memory resources can be saved as working memory load is reduced (Kirsh, 2010).

1.2.1 Investigations of offloading working memory processes

When conducting laboratory studies to investigate the offloading of working memory processes, different methods have been used. For instance, Kirsh and Maglio (1994) administered the video game “Tetris” to demonstrate how participants use cognitive offloading to lower working memory demands. When playing Tetris, the goal is to properly place shapes that fall from the top of the screen in order to complete a horizontal row of already placed shapes on the bottom of the screen. To do so, the player has the option to rotate as well as shift the shapes by pressing buttons. He or she can therefore try out different combinations in order to find the optimal orientation and positioning. When using the option to rotate the shapes, participants do not need to perform mental rotations that would fall back onto working memory. Kirsh and Maglio (1994) observed that participants used this option to offload working memory processes in order to improve task performance. Cognitive offloading simplified the Tetris task and therefore task performance was increased compared to solely relying on working memory. As another example, Cary and Carlson (2001) performed a study, in which the participants had to perform arithmetic tasks while being allowed to record notes (e.g., intermediate results). They investigated how participants are able to manage the distribution of task demands on external and internal resources. The participants frequently took notes instead of storing all relevant information in working memory. This offloading behavior decreased with more practice across several trials. Further, Cary and Carlson (2001) showed that the amount of cognitive offloading was related to the effort required to offload working memory processes. If there were less operational steps in terms of keys that needed to be pressed to take notes with a technical tool, more notes were taken than when there were more steps required. The participants therefore flexibly distributed their working memory demands on external and internal resources depending on the effort of cognitive offloading (Cary & Carlson, 2001). Similarly, Risko and Dunn (2015) showed that participants spontaneously offloaded verbal information (i.e. a presented string of letters) through note taking which they needed to remember for a subsequent recall. The amount of cognitive offloading increased with a larger amount of information that was presented. Risko and Dunn (2015) therefore concluded that individuals offload more when the load on working memory increases.

Another task that was successfully used to study the offloading of working memory processes is the Pattern Copy Task (formerly known as Blocks World Task; Ballard, Hayhoe, Li, & Whitehead, 1992; Ballard, Hayhoe, & Pelz, 1995). In the basic version of this task the participants have to replicate a pattern of colored squares that is displayed in a model window into an empty workspace window. First, the participants can inspect the pattern of colored squares in the model window and then they can reconstruct the pattern in the workspace window. They therefore move the corresponding colored squares from an additional resource window into the workspace window. The participants can always look up the pattern of colored squares by inspecting the model window again. In the first studies using the Pattern Copy Task, Ballard et al. (1992; 1995) observed that the participants tended towards a *minimal memory approach* indicating an extensive use of cognitive offloading (i.e. looking at the model window over and over again and memorizing only a small amount of information at once) over internal memorization (i.e. looking at the model window not so often and memorizing more information at once). They therefore concluded, that the participants did not operate at their maximum working memory capacity, but rather minimized working memory load by offloading working memory processes into the external environment. In follow-up studies Fu and Gray (2000, see also Gray, Sims, Fu, & Schoelles, 2006; Patrick et al., 2015; Waldron, Patrick, & Duggon, 2011) could not support this minimal memory approach but rather introduced a *soft constraints hypothesis* predicting optimal performance due to maximizing the expected gains of a strategy while minimizing the related costs. They observed that cognitive offloading depends on the associated temporal costs. Thus, when the opening of the model window was associated with high temporal costs (e.g., a delay of 1 second) the participants offloaded less than when there were low temporal costs. Therefore, the participants adapted their offloading behavior based on the associated temporal costs, rather than minimizing working memory load under all circumstances.

These studies show that participants adaptively use the option of offloading working memory processes across various tasks to lower working memory demands (Kirsh & Maglio, 1994; Risko & Gilbert, 2016). Researchers in the field of cognitive offloading have mostly either focused on the investigation of determinants of offloading behavior or consequences of cognitive offloading. Thus, there are two lines of research – determinants and consequences of cognitive offloading (Risko & Gilbert, 2016). In following chapters I will maintain this separation of two lines of research and describe studies investigating the determinants of cognitive offloading such as metacognitions as well as short-term and long-term consequences of offloading behavior.

1.3 Determinants of offloading working memory processes

Research on cognitive offloading has suggested several determinants of offloading working memory processes. These determinants can be separated into exogenous and endogenous factors. Exogenous factors refer to a person's external environment such as characteristics of materials and tools, whereas endogenous factors refer to a person's own internal cognition such as individual abilities and metacognitive beliefs that might affect offloading behavior. A recent review on cognitive offloading by Risko and Gilbert (2016) especially highlights the importance of metacognitions for the offloading of working memory processes.

Before I focus on the details of this specific subject – metacognitions as determinants of cognitive offloading – I will shortly describe other empirically observed determinants.

With regard to exogenous factors, the complexity as well as relevance (Schönpflug, 1986), difficulty (Hu, Luo, & Fleming, 2019) and amount of information that needs to be processed guide the offloading of working memory processes (Arreola, Flores, Latham, MacNew, & Vu, 2019; Gilbert, 2015a; Risko & Dunn, 2015). More complex, relevant and difficult information as well as a larger amount of information leads to more cognitive offloading. Furthermore, the number of operational steps required to offload working memory processes, affects offloading behavior (Cary & Carlson, 2001; O'Hara & Payne, 1998; Schönpflug, 1986). For instance, Schönpflug (1986) observed more printing out of information instead of memorizing it when printing required less operational steps than when more steps were required. Moreover, studies consistently showed that temporal costs related to accessing the relevant information impact offloading behavior (e.g., Fu & Gray, 2000; Gray et al., 2006; Patrick et al., 2015; Waldron et al., 2011). All those exogenous factors with regard to a person's external environment seem to affect situational cost-benefit considerations when performing a working memory task. Based on the associated costs and benefits of an offloading strategy, individuals decide to rely more or less on cognitive offloading (e.g., Cary & Carlson, 2001; Gray et al., 2006; Schönpflug, 1986).

Also, endogenous factors regarding a person's own internal cognition might affect offloading behavior. Onto this account, research has observed a relationship between one's own cognitive abilities and cognitive offloading (Gilbert, 2015b; Risko & Dunn, 2015). In experiments of Gilbert (2015b) the participants performed a prospective memory task that required them to remember delayed intentions while performing an ongoing task. In the first phase, the participants had to solely rely on their memory to remember the intentions whereas in a second phase they were allowed to offload the intentions by setting reminders. A better unaided memory performance of participants in the first phase was accompanied by fewer reminder setting (i.e. less cognitive offloading) in the second phase (Gilbert, 2015b). Similarly, in a working memory task participants' performance when being prohibited from offloading was negatively correlated with the likelihood to write down to-be-remembered information when this was allowed (Risko & Dunn, 2015). Thus, better unaided working memory abilities led to less offloading of working memory processes (Risko & Dunn, 2015).

1.3.1 Metacognitions as determinants of offloading working memory processes

Beyond actual abilities, the subjective beliefs of individuals might also guide offloading behavior (Arango-Muñoz, 2013; Risko & Gilbert 2016). Hence, metacognitions are a possible but not yet fully identified endogenous determinant of cognitive offloading. Metacognitions can be described as a person's cognition about cognitive processing, or in other words, *thinking about one's own thinking* (Flavell, 1979). Metacognitions include the beliefs and experiences someone has with regard to his or her cognitive performance as well as the control of one's cognition based on such beliefs and experiences (Flavell, 1979). Therefore, classical models of metacognitions describe two main functions: the monitoring and control of cognition (Garofalo & Lester, 1985; Nelson & Narens, 1990). Metacognitive monitoring comprises metacognitive knowledge and experiences that both contribute to metacognitive control (Efklides, 2008; Flavell, 1979). Metacognitive knowledge refers to one's general knowledge and beliefs about one's cognition and also about tasks, goals, and strategies (Flavell, 1979). For instance, metacognitive knowledge about one's own cognition reflects subjective beliefs about how reliable one's memory is (Flavell, 1979; Garofalo & Lester, 1985). Such metacognitive knowledge can be accounted as offline metacognitive monitoring as it is not necessarily related to an ongoing cognitive task but rather generally stored in long-term memory (Efklides, 2008). Metacognitive experiences, on the other hand, are any conscious experiences that individuals make when coming across a task (metacognitive experiences can occur during or after a task, but mostly occur while performing a task; Flavell, 1979) and therefore refer to online monitoring (Efklides, 2008). Metacognitive experiences influence metacognitive knowledge by adding, changing and/or deleting from it (Flavell, 1979), and in turn both metacognitive knowledge and experiences contribute to the controlling of one's cognition (Garofalo & Lester, 1985; Flavell, 1979). The controlling function of metacognitions is responsible for the planning of actions, selection and implementing of strategies as well as revising and discarding strategies, thus affecting one's cognitive processing (Garofalo & Lester, 1985; Nelson & Narens, 1990). While metacognitive controlling is informed by metacognitive monitoring, also metacognitive controlling informs metacognitive monitoring via metacognitive experiences (Efklides, 2008; Nelson & Narens, 1990). Thus, there is a constant information flow between the main two functions – monitoring and controlling – of metacognitions (Nelson & Narens, 1990).

When performing a working memory task and having access to a technical tool, individuals can decide whether to rely on internal working memory processing or to offload working memory processes into the technical tool at hand (Risko & Gilbert, 2016). This choice of different strategies induces an *extended selection problem* (Arango-Muñoz, 2013). In order to dissolve this problem, individuals have to make metacognitive decisions indicating which strategy to use (e.g., offloading or internal memorization). Individuals might have metacognitive feelings about whether they can solve the problem internally or not. Positive metacognitive feelings (e.g., feelings of knowing) might lead to relying on one's internal cognitive processing whereas negative metacognitive feelings (e.g., feelings of forgetting) might lead to relying on external resources (Arango-Muñoz, 2013). Following this argumentation, Risko and Gilbert

(2016) introduced *a metacognitive model of cognitive offloading.* This model claims that individuals choose whether to rely on cognitive offloading or internal memory based on metacognitive beliefs and experiences about one's abilities, a task and/or a strategy. Metacognitive beliefs and experiences then contribute to metacognitive control, and thus to the actual selection of a specific strategy such as cognitive offloading. For example, when a person thinks that his or her spatial memory is not reliable, he or she might rather use a navigation system to find the way. In turn, offloading behavior affects future decision-making and metacognitive monitoring via the evaluation of the applied strategy such as evaluating navigation system use as a successful strategy for way finding. Thus, the metacognitive model of cognitive offloading proposes a circuit claiming that metacognitions affect cognitive offloading and vice-versa (Risko & Gilbert, 2016).

To investigate this proposed model, initial studies tested the influence of metacognitive beliefs on offloading behavior. Studies focusing on mental rotation paradigms showed that participants adapt their offloading behavior based on the believed reliability of a technical tool (Weis & Wiese, 2018) and the believed benefit of an offloading strategy (Dunn & Risko, 2015). In a study of Weis and Wiese (2018), the participants were able to offload normalization processes when working with rotated stimuli by using a knob that rotated the presented stimuli. When the participants were instructed that the knob was less reliable than it actually was, they used the knob less often to normalize the rotated stimuli than when they were instructed about the actual reliability of the knob or not instructed about the knobs' reliability at all, while actual reliability did not differ between the conditions. Therefore, false metacognitive beliefs about the used technical tool impacted offloading behavior (Weis & Wiese, 2018). Furthermore, Dunn and Risko (2015) observed that participants tilted their head in order to externally normalize a rotated text when they thought that this offloading strategy benefits their reading performance although there actually was no such performance benefit (i.e. performance was similar when offloading was prohibited). This result indicates that the participants misperceived the benefit of cognitive offloading; however, false metacognitive beliefs guided offloading behavior (Dunn & Risko, 2015). Apart from such beliefs about tools and strategies, also metacognitive beliefs about one's internal cognitive abilities are suggested to be a crucial determinant of cognitive offloading (Arango-Muñoz, 2013; Risko & Gilbert, 2016).

In a prospective memory task, Gilbert et al. (2020) showed that participants set reminders for later intentions based on their underconfidence in their own memory abilities. Thus, participants set more reminders than it would have been necessary to support their performance. This can be seen as a metacognitive bias towards cognitive offloading. This bias can be eliminated by providing the participants with metacognitive advice on the actual effectiveness of a strategy (Gilbert et al., 2020). When the participants were informed about the effectiveness of cognitive offloading based on their performance at the beginning of a trial, the participants were able to offload in the most successful manner (e.g., offloading when it indeed benefited performance or no offloading when it did not benefit performance). On a correlational basis, studies using the same prospective memory task observed a negative correlation between metacognitive beliefs (measured by subjective performance estimations) and offloading behavior (Boldt & Gilbert, 2019; Gilbert, 2015b). The higher the participants rated their upcoming performance, the fewer external reminders they set to remember delayed intentions (i.e. the less they offloaded within this task). Thus, metacognitive beliefs about one's internal memory predicted offloading behavior, while also actual memory abilities predicted offloading behavior independently (i.e. metacognitions and actual abilities were not correlated themselves; Gilbert, 2015b). These findings were further extended by showing that one's subjective confidence in an unrelated task predicted offloading behavior in a prospective memory task (Gilbert, 2015b).

Similarly, Risko and Dunn (2015) observed, that participants write down to-be-remembered items based on their subjective performance estimations as well as actual working memory abilities. Therefore, also in this study more positive metacognitive beliefs about one's internal working memory performance as well as better actual abilities were associated with less cognitive offloading. Beyond that, Hu et al. (2019) observed that the relationship between actual memory abilities and the likelihood of offloading was mediated by metacognitive beliefs about one's internal abilities. In their experiments the participants had to study word pairs for a later memory test. These word pairs were also saved into the computer to access it in the subsequent memory test. During the memory test the participants rated their confidence in correctly recalling a word pair and then had the option to ask for help (i.e. to access the saved word pair in the computer). The participants estimated their own performance higher when their own unaided memory abilities were indeed better, and this accurate metacognitive estimation predicted participants' proportion of asking for help. Hu et al. (2019) therefore concluded that metacognitive beliefs about one's memory abilities are a key driver for cognitive offloading (i.e. asking for help instead of relying on one's memory in their study).

Although these first studies suggest that metacognitive beliefs play a determining role when offloading working memory processes, it is not yet fully identified how actual working memory abilities, metacognitive beliefs about one's working memory, and cognitive offloading interact with each other. While some studies observed that actual abilities and metacognitive beliefs about those internal abilities influenced offloading behavior independently of each other (Gilbert, 2015b), other studies observed a relationship between these factors and that the relationship of actual abilities and offloading was mediated via metacognitive beliefs (Hu et al., 2019). Further studies are needed to dissolve these conflicting results and to provide insights into the causal relationship of metacognitive beliefs and the offloading of working memory processes.

1.4 Consequences of offloading working memory processes through released internal resources

In order to successfully use cognitive offloading in different situations consequences of cognitive offloading need to be considered. Especially positive immediate consequences of cognitive offloading are highlighted in offloading research. Studies showed that the offloading of working memory processes into technical tools can increase immediate task performance in terms of speed and/or accuracy (Risko & Gilbert, 2016). Hence, with a large variety of different tasks (not exclusively working memory tasks) beneficial effects of cognitive offloading on immediate task processing were observed. For instance, cognitive offloading increased accuracy in arithmetic tasks (Carlson, Avraamides, Cary, & Strasberg, 2007; Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001; Pyke & LeFevre, 2011) as well as in prospective memory tasks (e.g., Boldt & Gilbert, 2019; Gilbert, 2015a). Further, in mental rotation paradigms with the possibility to offload mental rotation processes, cognitive offloading also improved accuracy (Chu & Kita, 2011) and accelerated task processing (Risko, Medimorec, Chisholm, & Kingstone, 2014). However, cognitive offloading with technical tools does not only have positive effects. The offloading of working memory processes can also induce negative effects on later cognitive performance such as memory recall.

1.4.1 Consequences of cognitive offloading on memory formation

Several investigations suggest that cognitive offloading leaves cognitive residues such as a reduced problem-solving ability or long-term memory performance after offloading. For instance, cognitive offloading interferes with subsequent problem solving, when the possibility to offload is not available anymore (Moritz, Meyerhoff, & Schwan, 2020; O’Hara & Payne, 1998;

van Nimwegen & van Oostendorp, 2009). In other words, internal problem solving without having the option to offload was more successful when offloading was also prohibited in a previously performed training phase than when offloading was allowed in the training phase. Further, studies focusing on spatial memory observed that using a navigation system when finding a way impairs route learning as well as subsequent scene recognition (Fenech, Drews, & Bakdash, 2010; for similar results see Gardony, Brunyé, Mahoney, & Taylor, 2013; Gardony, Brunyé, & Taylor, 2015). Negative consequences of offloading working memory processes were also observed considering the formation of long-term memory (Eskritt & Ma, 2014; Henkel, 2014; Kelly & Risko, 2019a; 2019b; Pyke & LeFevre, 2011; Sparrow, Liu, & Wegner, 2011). In experiments of Kelly and Risko (2019a; see Kelly & Risko, 2019b, for a similar version and results) the participants had to write down words that were presented auditorily. In a recall phase the participants then could rely on their external notes in the first three trials whereas on the fourth trial they were not allowed to use their notes but had to rely on their own memory. Half of the participants knew that they will not be able to use their notes on this last trial, but the other half believed that they would be able to use them again. Participants who thought they could rely on their notes recalled the lists of words from their memory worse than participants who knew about not being allowed to access their notes. Thus, the expectation to use an offloaded word list impaired internal memory formation for this information (Kelly & Risko, 2019a). Another interesting finding was reported by Sparrow et al. (2011). In their study the participants had to type trivia statements into a computer file while they believed either that the computer would save the file or that the file would be erased. Then, the participants had to recall as many statements as possible from their memory. They remembered less information when they thought the computer would save the file than when they thought that the file would be erased. Thus, the participants seem to forget information that they believe is available in technical tools (Sparrow et al., 2011).

These studies suggest, that cognitive offloading, compared to relying on internal memory, impairs the formation of subsequent long-term memory for the offloaded information. Nonetheless, the reported studies typically used a no-choice design that either prohibited the participants from offloading or forced them to offload (e.g., Eskritt & Ma, 2014; Henkel, 2014; Kelly & Risko, 2019a; 2019b; Sparrow et al., 2011). Such a forced offloading behavior does not necessarily have the same long-term consequences as a free choice offloading behavior (i.e. the participants can choose the extent of offloading). Onto this account, studies showed conflicting results based on the voluntariness of cognitive offloading (Barasch, Diehl, Silverman, & Zauberman, 2017; Henkel, 2014). In experiments investigating photo-taking in museums as a form of cognitive offloading, Henkel (2014) observed that forcing participants to take photos harmed their memory for the photographed images compared to just observing them. In contrast, voluntarily photo-taking in museums in the study of Barasch et al. (2017) enhanced subsequent memory for the photographed images compared to observing them. Therefore, consequences of free choice offloading behavior also need to be considered.

Studies using the Pattern Copy Task as a free choice offloading paradigm showed a trade-off between immediate benefits and subsequent risks of cognitive offloading. More cognitive offloading due to low temporal costs within the task led to a faster immediate task processing and less errors when rebuilding a pattern of colored squares, but also to a worse memory performance in a recall test compared to less offloading in a high temporal costs condition (Morgan, Patrick, Waldron, King, & Patrick, 2009; similar results were also observed by Morgan, Patrick, & Tiley, 2013; Waldron, Patrick, Morgan, & King, 2007). Also, the resumption of a trial (i.e. continuing to rebuild the pattern) after an interruption was worse when the participants offloaded more than when they offloaded less (Morgan, et al., 2009; Morgan, et al., 2013). However, in these experiments, participants' memory was tested immediately after offloading. Thus, after some trials of the task, the participants were prompted to rebuild the last edited pattern of colored squares from their memory (Morgan et al., 2009; Waldron et al., 2007). This immediate recall test might not have exceeded the duration of working memory maintenance; therefore, no long-term memory formation was necessary. Unlike this design, in real-life individuals often need to remember previously offloaded information at a later point of time. For instance, one might write down a shopping list, but then forget his or her shopping list at home. In this scenario one has to consult long-term memory to retrieve the offloaded information as well as possible. This raises the important question of how well individuals can remember the relevant information across a longer timescale after offloading freely.

On the one hand, offloading working memory processes might not be harmful for long-term memory formation when released internal cognitive resources are successfully used. When offloading working memory processes, internal working memory resources might be released and used to enhance overall task performance (Beitzel & Staley, 2015; Kirsh, 2010). On this account, released resources due to offloading might be used for a deeper processing of the relevant information at hand which in turn fosters memory acquisition (Craik & Lockhart, 1972; Craik, 2002). In this case released resources would enhance learning (Salomon, 1990; Sweller, van Merrienboer, & Paas, 1998) and cognitive offloading would be beneficial for long-term memory formation. On the other hand, another possibility is that released resources cannot be used to foster long-term memory. Then, the offloading of working memory processes would not be a promising approach to enhance memory, but instead rather decreasing offloading behavior and relying more on one's working memory might be a successful attempt. Thereby, reducing offloading behavior could be accounted as a desirable difficulty (Beitzel & Staley, 2015).

Desirable difficulties are conditions during learning that make learning temporarily more difficult (i.e. individuals produce more errors and are slower in memory acquisition) but these conditions lead to a more enduring and flexible learning (Bjork, 1994; Bjork & Bjork, 2011). Such desirable difficulties support learning by stimulating active cognitive processing and strengthening long-term memory formation (Bjork & Bjork, 2011). Onto this account, relying on one's working memory instead of offloading might be more cognitively demanding, but might also increase long-term memory formation. To the best of my knowledge, empirical evidence for either of these theories is lacking. It is therefore a promising attempt for future research to investigate the consequences of freely offloading working memory processes through released internal cognitive resources on the formation of long-term memory.

1.4.2 Consequences of cognitive offloading on unrelated task processing

The previous sub-chapters dealt with the consequences of cognitive offloading on immediate task processing in a task that allows offloading as well as the formation of long-term memory for the offloaded information. In addition to these consequences initial studies showed effects of cognitive offloading on the subsequent processing of new information or unrelated tasks. In experiments of Storm and Stone (2015) the participants had to study word lists for a later recall. When the participants offloaded a first list of words (i.e. saved the list in a computer file) before studying a second list, they recalled the second word list better than when they did not offload but memorize the first list. Released cognitive resources due to cognitive offloading could therefore be redirected towards other matters. This *saving-enhanced memory effect* shows that cognitive offloading facilitates the encoding and memorizing of new, relevant information. Importantly, this effect only arose when the saving process was reliable (i.e. the information was successfully offloaded). When the participants experienced failures in saving the computer file their memory performance for the second word list did not improve compared to not saving the file at all (Storm & Stone, 2015). These findings were replicated and extended by Runge, Frings and Tempel (2019; see also Runge, Frings, & Tempel, 2020) who additionally observed that offloading a word list into a computer file enhances performance in a subsequent, unrelated task. In an arithmetic task the participants solved more problems when they have previously offloaded a word list compared to when they could not offload it. Thus, cognitive offloading does not only induce a saving-enhanced memory effect but also a so-called *saving-enhanced performance effect*. Runge et al. (2019) concluded that cognitive offloading frees the participants' from needing to internally memorize all information and thus releases cognitive resources. In turn, these released resources can be used to enhance performance in a subsequent, unrelated task. It is therefore possible to redirect the released resources due to cognitive offloading to a subsequent task (Runge et al., 2019). What remains unclear is if released resources can also be redirected to a secondary task that is performed simultaneously.

1.5 Present research

Research on cognitive offloading has investigated determinants that influence the decision to offload cognitive processes as well as positive and negative consequences of offloading behavior. However, as the previous theoretical overview suggests, very heterogenous methods were used for these investigations and there are multiple open questions. To my best knowledge, nobody has investigated both – determinants as well as consequences of offloading working memory processes – with a systematic and homogenous approach. Therefore, in the present PhD-project I aimed at systematically testing metacognitions as a key driver of cognitive offloading and consequences of offloading behavior through released internal resources with one paradigm.

In four studies I tackled the open questions derived from previous research to gain more knowledge on the offloading of working memory processes.

With regard to the determinants of cognitive offloading, I first proposed to follow up on the conflicting results regarding the relationship between metacognitions, actual working memory abilities, and the offloading of working memory processes in a correlational study (Study 1). The metacognitive model of cognitive offloading suggests a causal influence of metacognitions on cognitive offloading (Risko & Gilbert, 2015). Therefore, in an experimental study I additionally aimed at testing if metacognitive beliefs about one's working memory abilities causally impact the offloading of working memory processes (Study 2). In this study, I manipulated participants' metacognitive beliefs with fake performance feedback in order to test their impact on offloading behavior. Together, the correlational study as well as the experimental study served to identify metacognitions as determinants of offloading behavior. Knowledge about determinants of cognitive offloading helps to understand why individuals often offload cognitive processes into technical tools these days. Furthermore, such knowledge is necessary in order to alter cognitive offloading in situations that require more or less offloading.

With regard to the consequences of cognitive offloading, I focused on the effects of offloading on the formation of long-term memory as well as on the processing of a simultaneous secondary task. Thus, in the third study I investigated the former – consequences of offloading working memory processes on subsequent long-term memory – with three experiments. Thereby, I aimed at reinvestigating the suggested trade-off of cognitive offloading, namely enhanced immediate task processing but reduced memory performance due to the offloading of working memory processes (Morgan et al., 2009; Waldron et al., 2007). Importantly, different to previous research, in my study participants' memory was tested after a retention interval exceeding working memory maintenance. This procedure ensured that participants had to rely on long-term memory to recall the offloaded information in the subsequent memory test. Further, I also tested the use of potentially released cognitive resources due to cognitive offloading for the intentional formation of long-term memory. Moreover, I investigated the consequences of cognitive offloading for the formation of long-term memory representations when participants did not have the option to reduce offloading behavior (i.e. they were forced to offload maximally). With these experiments I systematically tested whether cognitive offloading can be used to foster long-term memory through released internal resources or if cognitive offloading is detrimental for long-term memory acquisition under all circumstances (i.e. offloading should be reduced to foster learning if possible). Beyond using released cognitive resources due to cognitive offloading for long-term memory formation, such released resources can also affect performance in other, unrelated tasks (Runge et al., 2019). In the final study I therefore aimed at testing the effects of cognitive offloading on the processing of a simultaneous secondary task through released cognitive resources (Study 4).

Together, the four studies proposed in my PhD-project provide a package of experiments that systematically investigated the offloading of working memory processes (see Table 1). For this systematic investigation I used a previously established offloading paradigm – the Pattern Copy Task. The Pattern Copy Task measures free choice offloading behavior and thus aims at reflecting offloading behavior in real-life. In the next chapters, I will describe the proposed studies in more detail before discussing the findings at the end of this PhD-thesis. The following chapters are written as separately readable manuscripts. This results in overlapping contents with this introduction as well as between the empirical chapters.

Table 1. *Overview of Studies in the Present PhD-Project*

Metacognitions as determinants of offloading working memory processes		
Study 1	Correlational study	*N* = 80
Study 2*	Fake performance feedback	*N* = 159
Consequences of offloading working memory processes trough released internal resources		
Study 3	Trade-off of cognitive offloading	*N* = 172
	Intentional long-term memory formation	*N* = 172
	Forced cognitive offloading	*N* = 172
Study 4	Secondary task performance	*N* = 133

* Study 2 is included in a manuscript under revision (Grinschgl, Meyerhoff, Schwan, & Papenmeier, under revision).

Declaration regarding collaborative publications/manuscripts

The following chapter (Chapter 2) consists of a manuscript that was authored by me and is not published. I am thankful to Clara Deinhart, Rebekka Hemmrich, Lea-Judith Herschbach, and Paula Rehm for their help in conducting this study.

Title of paper: *The relationship of metacognitions, working memory, and cognitive offloading*
Status in publication process: Not published.

2. Study 1

– The relationship of metacognitions, working memory, and cognitive offloading –

Today, humans can usually access modern technical tools such as smartphones or tablets which allow the externalization of cognitive processes. For instance, individuals can externalize memorization such as saving an appointment in a smartphone's calendar instead of memorizing it. This externalizing behavior is referred to as *cognitive offloading* (Risko & Gilbert, 2016). Cognitive offloading supports cognitive processing by lowering cognitive demands through externalizations (Risko & Gilbert, 2016). Further, due to offloading behavior individuals can overcome limitations of internal cognitive processing (Risko & Gilbert, 2016) and internal cognitive resources are released (Kirsh, 2010). Especially working memory is a strictly limited cognitive system (Baddeley, 1992; Luck & Vogel, 2013), but with the help of cognitive offloading capacity limitations of working memory can be overcome (Risko & Gilbert, 2016; Wilson, 2002). Therefore, offloading behavior can support performance in working memory tasks (Risko & Gilbert, 2016) and improve cognition (Kirsh, 2010).

Previous studies showed that individuals' extent of offloading working memory processes varies with the perceived relation between costs during offloading and the expected benefits due to the released resources (Cary & Carlson, 2001; Gray, et al., 2006; Schönpflug, 1986). If technical tools are more costly to use in terms of required physical actions or temporal costs, individuals offload less working memory processes into these tools and rely more on their internal working memory resources. Onto this account, research addressing cognitive offloading mostly has focused on the role and the design of the technical tool at hand (Cary & Carlson, 2001; Gray et al., 2006; Schönpflug, 1986), however, characteristics of the users that result in individual differences in offloading behavior have not yet been fully identified. A good candidate for such a source of inter-individual variance in the amount of cognitive offloading are metacognitive beliefs with regard to one's memory abilities (Arango-Muñoz, 2013; Risko & Gilbert, 2016). Metacognitive beliefs might motivate some individuals to rely on internal working memory resources whereas other individuals might prefer to rely on external resources such as the technical tool at hand (Arango-Muñoz, 2013). For instance, if an individual considers his or her working memory capacity to be high, he or she might rely less on offloading strategies as they appear to be unnecessary. Another individual who considers his or her working memory to be low, however, might prefer to take advantage of the possibility to offload working memory processes as a compensatory strategy. Thus, metacognitions might be a key factor that drives the decision to offload working memory processes. The present study addresses this proposed influence of metacognitive beliefs on the offloading of working memory processes.

Metacognitions and Cognitive Offloading

Metacognitions describe individuals' *thinking about their own thinking* (Flavell, 1979). Thereby, metacognitions can be separated into metacognitive knowledge and metacognitive experiences. Metacognitive knowledge refers to one's general knowledge and beliefs about one's cognitive abilities, tasks, and strategies. Hence, metacognitive beliefs about one's working memory can be accounted as metacognitive knowledge and can be seen as offline metacognitive monitoring (i.e. it is not necessarily related to an ongoing task; Efklides, 2008; Flavell, 1979). Metacognitive experiences, on the other hand, are related to ongoing experiences while performing a task and thus refer to online metacognitive monitoring. Both – metacognitive knowledge and experiences – are supposed to influence the control of one's cognition via selecting or discarding specific strategies (Efklides, 2008; Flavell, 1979). Onto this account, metacognitions might determine the use of cognitive offloading as a strategy to perform a working memory task.

Arango-Muñoz (2013) introduced the *extended selection problem* dealing with the decision to offload cognitive processes into the available technical tool. He argues that this decision is motivated by individuals' metacognitive beliefs such as feelings of knowing (Arango-Muñoz, 2013). In a similar vein, Risko and Gilbert (2016) proposed the *metacognitive model of cognitive offloading* stating that cognitive offloading is guided by metacognitive beliefs and experiences. Based on subjective estimations about one's abilities and/or properties of strategies, tools, and tasks at hand, individuals decide whether to offload cognitive processes or not (or the extent of cognitive offloading). Initial studies investigating metacognitions as determinants of cognitive offloading, observed that metacognitive beliefs about one's abilities indeed influence offloading behavior on a correlational basis (Boldt & Gilbert, 2019; Gilbert 2015b; Risko & Dunn, 2015; Hu et al., 2019). In a prospective memory paradigm, Gilbert (2015b) observed that more reminder setting for future intentions was associated with fewer positive beliefs about one's memory performance (for similar results see Boldt & Gilbert, 2019). Also, when needing to remember verbal stimuli, Risko and Dunn (2015) observed more cognitive offloading (i.e. writing down relevant information) when the participants estimated their unaided memory performance worse. These studies therefore suggest that less positive beliefs about one's own memory lead to more cognitive offloading. In addition, they also observed that actual memory abilities influence offloading behavior (Gilbert, 2015b; Hu et al., 2019; Risko & Dunn, 2015). A better unaided memory performance of participants (i.e. when the task did not allow the offloading of cognitive processes) was associated with less cognitive offloading (Gilbert, 2015b; Risko & Dunn, 2015). This finding raises the question of whether actual abilities influence cognitive offloading directly or whether this influence is mediated via metacognitive beliefs. In the study of Gilbert (2015b), he observed the former – namely, a direct influence of actual abilities on cognitive offloading, independently of metacognitive beliefs. Actual abilities and metacognitive beliefs were not correlated themselves while they were both correlated with offloading behavior (Gilbert, 2015b; see also Risko & Dunn, 2015). Contrary, using a different paradigm Hu et al. (2019) observed that actual abilities influenced offloading behavior via metacognitive beliefs. In this study the participants had to remember word pairs for a later recall. At a memory test, the participants then could choose to either rely on their working memory to retrieve the before studied word pairs or to ask for help (i.e. look up the relevant information in a technical tool). Hu et al. (2019) observed that both actual memory performance and metacognitive beliefs about one's performance as measured by performance estimations predicted cognitive offloading (i.e. asking for help proportion). However, additional analyses revealed that the influence of actual abilities on cognitive offloading was mediated by metacognitive beliefs. Thus, the participants were able to correctly monitor their own abilities and in turn to adapt offloading behavior accordingly. Additionally, Meeks, Hicks and Marsh (2007) reported that participants have a basic metacognitive awareness, although, metacognitive beliefs about one's memory abilities do not always absolutely match their actual abilities.

To conclude, the described studies to not provide consistent findings with regard to metacognitions as a key driver of cognitive offloading. It remains unclear how actual abilities, metacognitive beliefs about one's abilities, and offloading behavior interact with each other. To further investigate the relationship between these factors – metacognitive beliefs, actual abilities, and cognitive offloading – I tested their interplay in a correlational study.

Present Study

In the present study I administered the Pattern Copy Task to measure cognitive offloading. The Pattern Copy Task is a working memory paradigm that allows the individual offloading of working memory processes by looking up relevant information in a technical tool (e.g., Gray et al., 2006). Before the participants performed this task, I assessed participants' metacognitive beliefs about their general memory abilities with a multifactorial memory questionnaire (MMQ; Troyer & Rich, 2002). Additionally, the participants provided a performance estimation prior to performing the Pattern Copy Task ask as an index of specific metacognitive beliefs about one's working memory abilities within this task. Thus, I collected two indicators of participants' metacognitive beliefs – the MMQ for general metacognitive beliefs and the performance estimation for specific metacognitive beliefs. Then I measured cognitive offloading in the Pattern Copy Task and working memory capacity with two additional working memory tasks.

I predicted, that the participants would accurately estimate their working memory abilities and in turn select a proper strategy to perform the Pattern Copy Task (i.e. more offloading when one's working memory is worse). More specifically, I predicted a positive correlation between actual working memory capacity and metacognitive beliefs (measured by the MMQ and the performance estimation). Further, I predicted a negative correlation between actual working memory capacity and cognitive offloading. I also predicted a negative correlation between metacognitive beliefs and offloading behavior. The more positive metacognitive beliefs individuals have about their own working memory, the less they should offload in the Pattern Copy Task. As the next step I aimed at testing a mediation effect, namely if the relationship between actual working memory capacity and cognitive offloading is mediated by metacognitive beliefs about one's working memory (see Figure 1). If individuals monitor their working memory abilities correctly, they might choose a proper amount of offloading working memory processes. Hence, metacognitive beliefs might mediate the influence of working memory capacity on offloading behavior. For exploratory purposes, I also calculated *absolute monitoring accuracy* as an index of under- and overconfidence of participants in their working memory abilities.

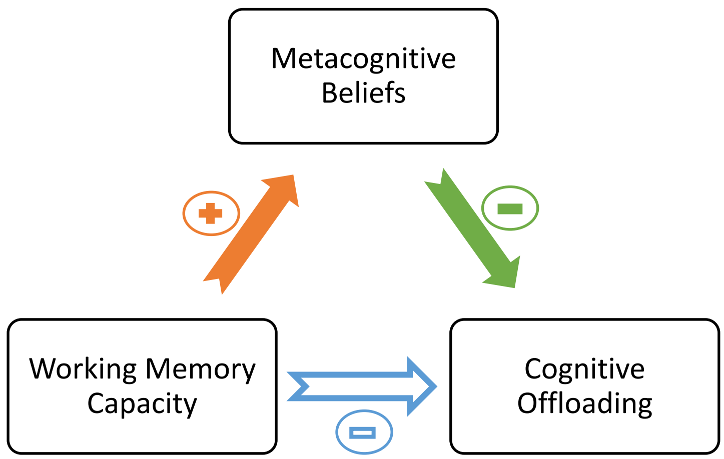

Figure 1. Illustration of expected relationship between metacognitive beliefs about one's working memory (measured by the MMQ and the performance estimation), working memory capacity (measured by two working memory tasks), and cognitive offloading (measured by the Pattern Copy Task) in Study 1.

Method

This study was preregistered with regard to its hypothesis, independent and dependent variables, sample size, statistical analyses, and exclusion criteria. The preregistration can be accessed on the Open Science Framework (https://osf.io/gv58s/?view_only=7b26f554f2df4e26a4d946c00810086f).

Participants

In order to achieve a statistical power of $(1- \beta) = .90$ and to detect small to medium effect sizes of $f = 0.15$ my final sample included 80 participants (62 female, 18 male; age 18 - 29 years, $M_{age} = 21.81$, $SD_{age} = 2.42$). Based on the preregistered exclusion criteria I excluded and replaced participants due to missing data (6) and too large deviations (+/- 3 *SD*) of the mean of the dependent variables (4). Further, I excluded and replaced one participant due to not sufficient German language skills and one participant due to a reported red-green deficiency. All participants provided informed consent and were reimbursed for their participation with course credits or financial compensation. The study was approved by the ethics committee of the Leibniz-Institut für Wissensmedien.

Apparatus

I used 12.3'' Microsoft Surface Pro Tablets (2736 x 1824 pixels) for the performance of all computerized tasks. The tablets were lying flat on the table at a viewing distance of around 36 cm. The participants used the tablets' touch function to perform the tasks which were controlled by PsychoPy scripts (Peirce, 2007).

Procedure

At the beginning of the study the participants answered an adapted version of the MMQ. Thereafter, they read the instruction of the Pattern Copy Task (including visual examples). Then, the participants had to estimate their upcoming performance in the Pattern Copy Task in terms of how many colored squares they are able to memorize at once. Following this subjective estimation, the participants performed the Pattern Copy Task in which they had to rebuild a pattern of colored squares. Afterwards, the participants conducted two working memory tasks, the Visual Patterns Test and the Digit Span Task. The whole study took approximately 60 minutes.

Paper and pencil tasks

Multifactorial Memory Questionnaire. The MMQ is a questionnaire about one's general memory abilities. I shortened and translated the original version from Troyer and Rich (2002) so that it contained 18 statements in German. The adapted questionnaire included statements measuring how someone feels about his or her memory abilities such as "*I am generally pleased with my memory abilities*". The participants rated their agreement with each statement on a 5-point Likert scale (strongly agree to strongly disagree). With this questionnaire I aimed at measuring metacognitive beliefs about one's general memory abilities. Therefore, I averaged all 18 ratings (higher values indicate more positive beliefs about one's memory).

Performance estimation. After reading the instruction to the Pattern Copy Task and seeing pictures as examples of the task, the participants had to estimate their upcoming memory performance within this task. They did so by providing an indicator of how many colored squares (including the correct color and exact position) they can remember (i.e. internally store) and correctly rebuild at once. This estimation was supposed to capture task-specific metacognitive beliefs about one's working memory abilities.

Computerized tasks

Pattern Copy Task. In this study I used the Pattern Copy Task to measure cognitive offloading (e.g., Fu & Gray, 2000; Gray et al., 2006). The participants had to rebuild a pattern of twelve colored squares displayed in a model window on the left side of the tablet screen in an empty workspace window on the right side of the screen (see Figure 2). In the model window the colored squares were randomly arranged in a 5 x 5 grid of empty squares (2.52 x 2.52 deg each). I used the colors blue, orange, red, cyan, green, dark green, yellow, bisque, sienna, purple, pink, and gray (no color was repeated). The workspace window consisted of a 5 x 5 grid of empty squares. To rebuild the pattern the participants had to drag and drop the colored squares from an additional resources window on the lower right side of the tablet screen into the workspace window. Gray masks covered the windows and only either the model window or the workspace and resource window could be opened at a time. The participants could open the model window by moving a slider from its right towards the left side of the screen and the workspace and resource window by clicking on a bar to their left. They could either open the model window to look at the pattern of colored squares or the workspace and resource window to rebuild the pattern. They could switch between the windows whenever and at any time. When the participants correctly rebuilt the pattern of colored squares in the workspace window, they were able to end the trial and to proceed to the next trial by pressing an “End Trial”-button. If the pattern was not correctly rebuilt, the participants were requested to further edit it. The participants completed five practice trials and 20 test trials of this task. I measured cognitive offloading with two variables: the number of openings of the model window and the number of correctly copied items after the first opening of the model window. The first opening is independent of any other opening and thus a good indicator of cognitive offloading. More openings of the model window and a lower number of initially correctly copied items indicate more cognitive offloading and less internally memorized information.

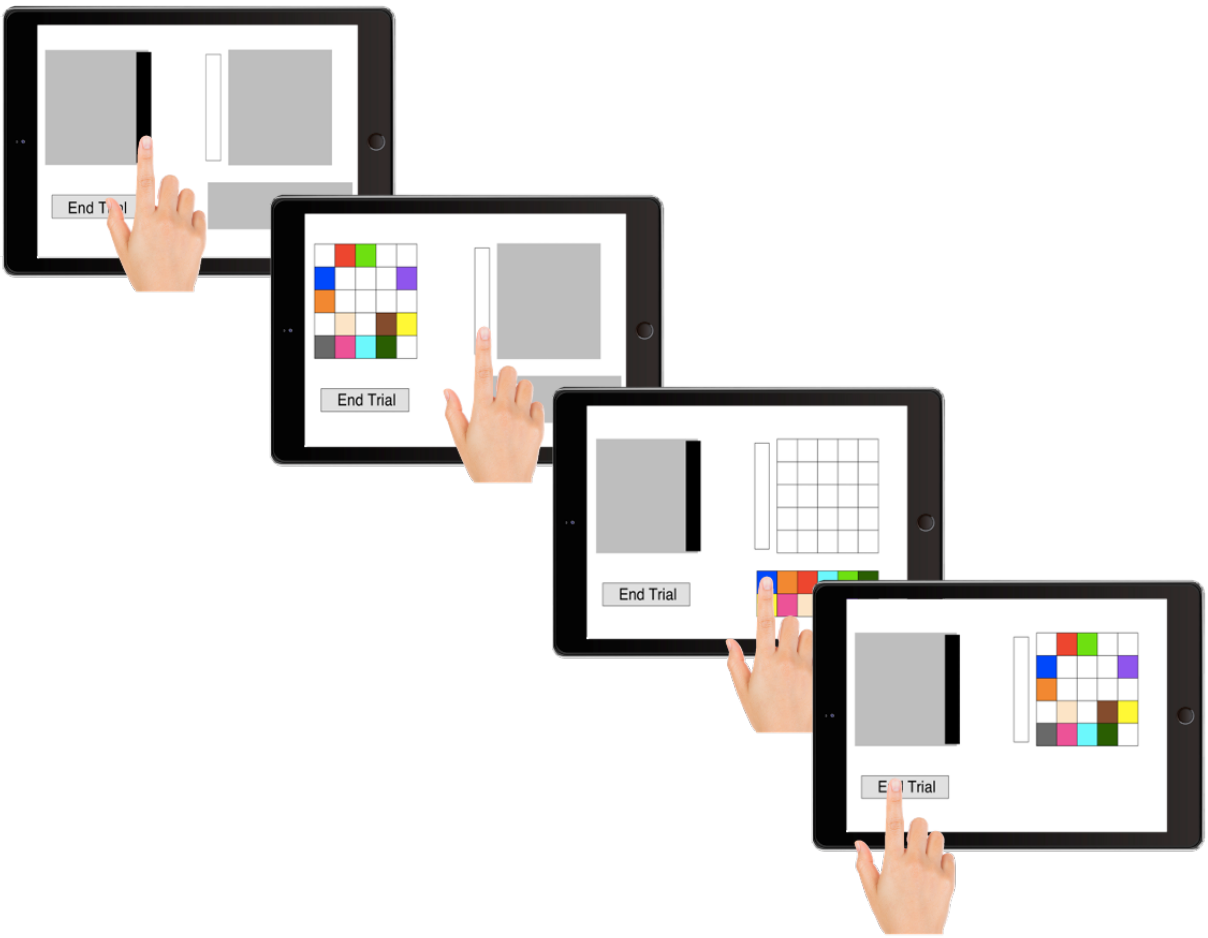

Figure 2. Illustration of the Pattern Copy Task measuring the offloading of working memory processes. The participants had to rebuild a pattern of colored squares from the left side of the screen (model window) into the workspace window on the right side of the screen. Therefore, they dragged and dropped the colored squares from an additional resource window (lower right side) into the workspace window. The participants could switch between the model and workspace window as often as they wanted, but they were never visible at the same time. (Tablet frame was designed by Freepik; hand was designed by Janoon028/Freepik.)

Visual Patterns Test. The Visual Patterns Test was used to measure visuospatial working memory capacity (see Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999, for a similar version). In this task, the participants observed a spatial arrangement of colored squares for three seconds (see Figure 3a). The colored squares were arranged in a 5 x 5 grid of empty squares (2.52 x 2.52 deg each) and could have the following colors: blue, orange, red, cyan, green, yellow, sienna, purple, pink, and gray. After the three-second presentation phase, the participants had to reconstruct the pattern of colored squares from their memory by dragging them from the right side of the screen into an identically shaped empty grid. The task followed an adaptive staircase of difficulty. The participants started the task with a grid filled with two colors. The set size increased when the pattern was reconstructed correctly (+ 1 square, with a maximum of 10 squares, whereby no participants achieved the maximal capacity) and decreased when it was not correctly reconstructed (- 1 square, with a minimum of 2). The participants performed 30 trials of this task. As an index of visuospatial working memory capacity, I averaged the set size (i.e. number of squares) of the last 10 correctly solved trials.

Digit Span Task. The Digit Span Task was used to measure non-spatial working memory capacity (see Paul et al., 2005, for a similar version). In this task, the participants observed a sequence of single digits (selected from 0 - 9) each presented for one second and separated by a fixation cross for 0.3 seconds (see Figure 3b). After the presentation, the participants had to reproduce the sequence of digits by pressing the numbers on the tablet screen one after another. After a correct reproduction, the number of presented digits increased by one (starting with 2 digits and a maximum of 20 digits, but no participant achieved this maximum capacity). Following an incorrect reproduction, the number of presented digits decreased by one digit (with a minimum of 2 digits). The participants performed 30 trials of this task. As a measure of non-spatial working memory capacity, I averaged the number of presented digits of the last ten correctly solved trials.

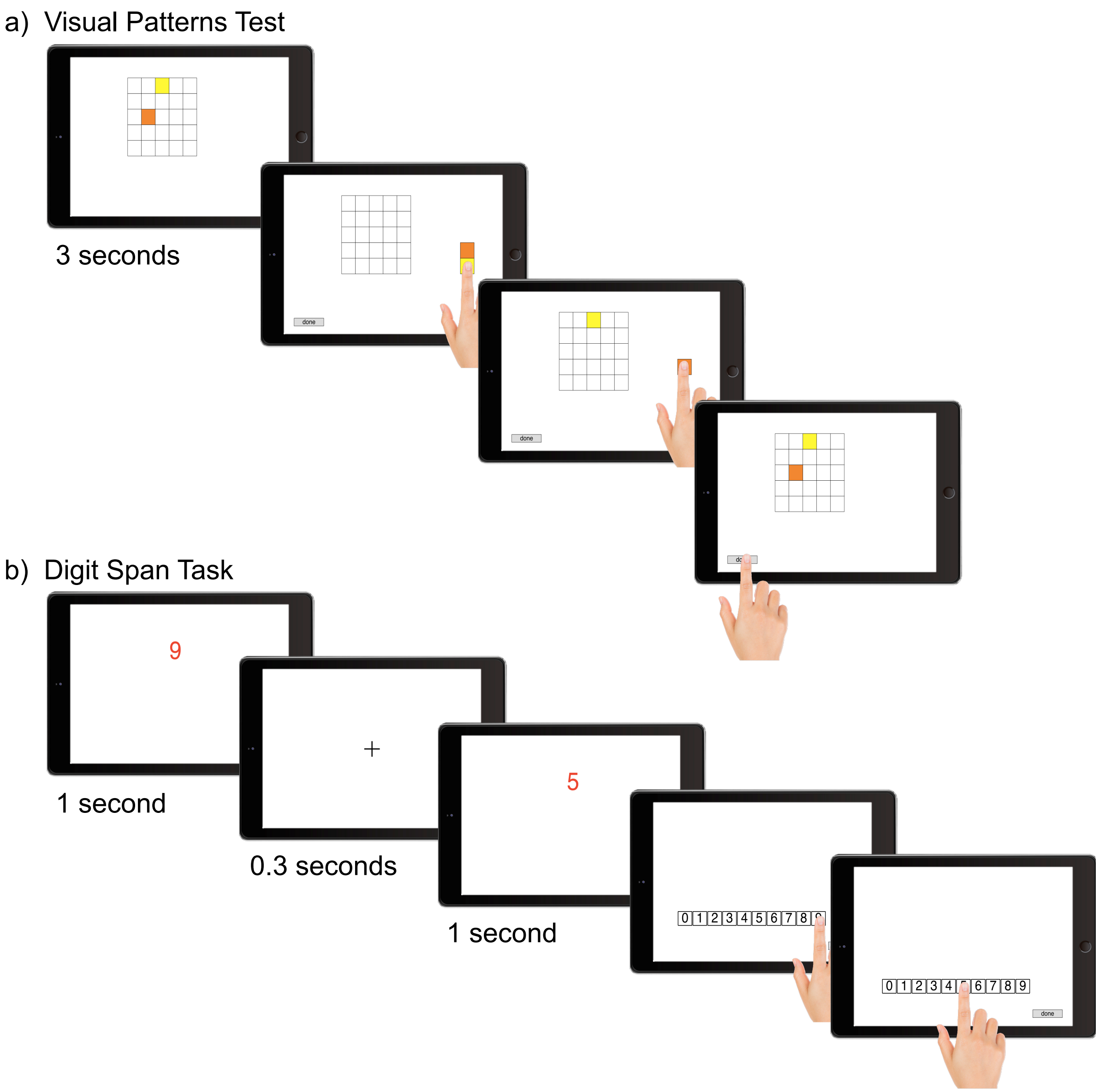

Figure 3. Illustration of Visual Patterns Test and Digit Span Task, both measuring working memory capacity. a) In the Visual Patterns Test, the participants had to reconstruct a spatial arrangement of colored squares after a three-second presentation phase. b) In the Digit Span Task, the participants observed a sequence of digits (each digit presented for 1 second with a 0.3 second interim period) and then had to repeat this sequence. Please note that the fixation cross is not displayed in its' original scale for illustrative purposes. (Tablet frame was designed by Freepik; hand was designed by Janoon028/Freepik.)

Results

Working memory capacity and cognitive offloading

Pearson-correlations showed a significant relationship between working memory capacity and cognitive offloading across all variables, all $|r(78)\text{s}| >= .31$, all *p*s <= .001 (see Table 2). The higher participants' actual working memory capacity measured by the Visual Patterns Test and the Digit Span Task was, the less they offloaded within the Pattern Copy Task (i.e. the fewer times they opened the model window and the more items they copied initially correct).

Table 2. *Correlations of Working Memory Capacity and Cognitive Offloading*

	Openings of the Model Window	**Initially Correctly Copied Items**
Capacity in Visual Patterns Test	r (78) = -.49, p <.001	r (78) = .43, p <.001
Capacity in Digit Span Task	r (78) = -.31, p <.001	r (78) = .35, p =.001

Working memory capacity and metacognitive beliefs

With regard to metacognitive beliefs about one's general memory capacity (measured by the MMQ) Pearson-correlations revealed no significant relationship with working memory capacity, all $r(78)$s <= -.04, all *p*s >= .705. Further, specific metacognitive beliefs (measured by the performance estimation) were not significantly correlated with working memory capacity, all $|r(78)\text{s}| <= .11$, all *p*s >= .325. Therefore, I did not receive evidence for metacognitive accuracy calculated as the relationship between actual working memory abilities and predicted performance across participants (see Table 3).

Table 3. *Correlations of Working Memory Capacity and Metacognitive Beliefs*

	MMQ	**Performance Estimation**
Capacity in Visual Patterns Test	r (78) = -.03, p =.812	r (78) = -.11, p =.325
Capacity in Digit Span Task	r (78) = -.04, p =.705	r (78) = .005, p =.956

Metacognitive beliefs and cognitive offloading

To investigate the third relationship between metacognitive beliefs and cognitive offloading, I again performed Pearson-correlations (see Table 4). I observed no significant correlation between general metacognitive beliefs and the number of openings of the model window in the Pattern Copy Task, $r(78) = .22$, $p = .054$, whereas general metacognitive beliefs were significantly correlated with the number of initially correctly copied items, $r(78) = -.24$, $p = .032$. However, this correlation did not follow the expected direction (i.e. less cognitive offloading when participants' metacognitive beliefs are higher). Instead, higher ratings about one's general memory abilities were accompanied by more cognitive offloading (as measured by initially correctly copied items). There was no significant correlation between specific metacognitive beliefs and cognitive offloading, all $r(78)$s <= .12, all ps >= .271.

Table 4. *Correlations of Metacognitive Beliefs and Cognitive Offloading*

	MMQ	**Performance Estimation**
Openings of the Model Window	r (78) = .22, p =.054	r (78) = .12, p =.271
Initially Correctly Copied Items	r (78) = -.24, p =.032	r (78) = .04, p =.689

Mediation analyses

Unexpectedly, I found no relationship between working memory capacity and metacognitive beliefs. Further, I also found no distinct relationship between metacognitive beliefs and cognitive offloading. Due to this lack of significant correlations between working memory capacity and metacognitive beliefs (and in parts between cognitive offloading and metacognitive beliefs) no mediation analyses could be performed.

Overconfidence (exploratory)

To further investigate participants' metacognitive accuracy, I used the difference of the metacognitive performance estimation (i.e. how many colored squares one beliefs he or she can copy at once) and working memory capacity measured by the Visual Patterns Test (i.e. how many colored squares one actually is able to correctly memorize at once) to determine absolute metacognitive accuracy. Positive values suggest overconfidence whereas negative values suggest underconfidence. Indeed, 86.25% of the participants were overconfident. On average the participants estimated to correctly reproduce 1.6 items ($SD = 1.73$) more than their visuospatial working memory capacity as measured by the Visual Patterns Test allowed (12.5% of the participants where underconfident, 1.25% showed perfect absolute metacognitive accuracy).

Discussion

The present study investigated the interplay of metacognitive beliefs about one's working memory, actual working memory capacity, and the offloading of working memory processes in the Pattern Copy Task. I observed that working memory capacity is negatively correlated with offloading behavior. Thus, the higher participants' actual working memory capacity was, the less they offloaded. Unexpectedly, actual working memory capacity was not related to metacognitive beliefs about one's working memory. This finding indicates that the participants did not correctly evaluate their own abilities (i.e. there seems to be a lack of monitoring accuracy). Furthermore, I also did not observe a distinct relationship between metacognitive beliefs about one's working memory and cognitive offloading. While specific metacognitive beliefs about one's working memory (measured by a performance estimation) were not correlated with offloading behavior at all, general metacognitive beliefs provided mixed findings. General metacognitive beliefs were not significantly correlated with the number of openings of the model window in the Pattern Copy Task, however, they were correlated with the number of initially correctly copied items. The higher the participants rated their general memory abilities, the less items they copied correctly after the first opening of the model window (i.e. the more they offloaded). This relationship did not follow the expected direction (i.e. less offloading with more positive metacognitive beliefs), but rather the participants offloaded more when they thought that their general memory abilities were higher. Due to these inconclusive results I cannot confirm that metacognitive beliefs act as a predictor of cognitive offloading. Furthermore, no mediation analyses could be conducted because of the lack of correlation between actual working memory capacity and metacognitive beliefs, as well as the unclear relationship between metacognitive beliefs and offloading behavior.

To follow-up on these results, I took a closer look at the participants' monitoring accuracy (i.e. how accurate they estimated their own performance). On the one hand, monitoring accuracy can be indicated as the relationship between metacognitive estimations and actual abilities such as the calculated correlation of metacognitive beliefs and working memory capacity. This correlation is called *relative monitoring accuracy* (Kelemen, Frost, & Weaver, 2000; Schraw, 2009) and did not yield a high monitoring accuracy in my study (i.e. there was no correlation).

On the other hand, the so-called *absolute monitoring accuracy*[1] can be used to indicate over- and underconfidence of one's memory abilities. Absolute monitoring accuracy is calculated as the difference of metacognitive estimations and actual abilities (Kelemen et al., 2000; Schraw, 2009). As an index of absolute monitoring accuracy, I calculated the difference of specific metacognitive beliefs indicating how many colored squares one thinks he or she can remember at once (see "performance estimation") and working memory capacity of the Visual Patterns Test indicating how many visual objects (i.e. colored squares) one can actually store in working memory. Interestingly, most participants in my study were overconfident (86.25 %). They thought that they would be able to remember more colored squares than they actually could. Thus, with regard to both indicators – relative and absolute monitoring accuracy – I observed a lack of monitoring accuracy in my study. I hypothesized that when participants are able to accurately estimate their own performance (i.e. there is a monitoring accuracy) they might be able to select the proper strategy to perform the Pattern Copy Task (e.g., more offloading when one's working memory is worse). In contrast, I actually did not observe monitoring accuracy within my study and even false metacognitive beliefs did not guide offloading behavior.

The findings of the present study contradict previous research that indeed observed a relationship between metacognitions and offloading behavior (Boldt & Gilbert, 2019; Gilbert, 2015b; Risko & Dunn, 2015; Hu et al., 2019). However, what is in line with previous studies is the relationship between actual working memory abilities and cognitive offloading (Gilbert, 2015b; Risko & Dunn, 2015). The higher participants' actual working memory capacity was, the less they offloaded. Therefore, actual working memory abilities seem to be a strong predictor for cognitive offloading. Onto this account, the participants might have experienced how good they

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[1] Absolute monitoring accuracy is sometimes also referred to as *metacognitive bias* (Kelemen et al., 2000; Schraw, 2009).

are in performing the Pattern Copy Task based on their actual working memory abilities and in turn adapted their offloading behavior accordingly (e.g. more offloading when one's working memory is poor). What remains unclear is how metacognitive beliefs contribute to the offloading of working memory processes within the Pattern Copy Task. The present study indicates that (false) metacognitive beliefs are not related to cognitive offloading as suggested. Nonetheless, I propose to further systematically investigate how metacognitive beliefs might contribute to the offloading of working memory processes. Beyond the correlational approaches of previous studies (e.g., Gilbert et al., 2015b, Hu et al., 2019) I especially propose to test the causal impact of metacognitive beliefs on offloading behavior in experimental studies.

Despite the lack of a distinct relationship between metacognitive beliefs and cognitive offloading, also metacognitive beliefs and actual working memory abilities were not related in this study. Unlike the findings of Hu et al. (2019), but similar to results of Gilbert (2015b), the participants did not correctly estimate their own working memory abilities. Instead, I observed that the vast majority of participants was overconfident. Overconfidence in one's abilities and performance was commonly observed across various research regarding metacognitions (e.g., Callender, Franco-Watkins, & Roberts, 2016; De Bruin, Kok, Lobbestael, & de Grip, 2017; Koriat & Bjork, 2005). For instance, Koriat and Bjork (2005) observed that individuals' metacognitive monitoring suffers from failures in estimating one's abilities. These failures induce a sense of confidence in one's performance, thus leading to overconfidence. Metacognitive accuracy and in turn strategy selection can be improved by metacognitive advice or metacognitive training (Gilbert et al., 2020; Callender et al., 2015; Ghatala, 1986). In a prospective memory paradigm Gilbert et al. (2020) showed that participants' strategy selection can be improved by providing the participants with metacognitive advice suggesting which strategy to solve the task is the most promising one. Metacognitive advice led to optimal offloading behavior that helped to maximize task performance. Similarly, Ghatala (1986) provided children with feedback on adequate strategies to perform a task which enhanced successful strategy selection. Thus, feedback can increase metacognitive accuracy and support the selection of a proper strategy when performing a task (Callender et al., 2015; Ghatala, 1986). Onto this account, it might also be possible to enhance metacognitive accuracy with regard to the Pattern Copy Task by providing participants with feedback or metacognitive advice.

Another reason for the lack of metacognitive accuracy in my study might be the study design. In my study, the participants estimated their working memory performance before gaining any experiences in the Pattern Copy Task. Thus, after only reading the instruction of the task the participants estimated their upcoming performance. This method served to collect metacognitive estimations that only reflect the participants' subjective beliefs and not actual experiences. However, this is different to previous studies investigating metacognitions in the context of cognitive offloading. In the previous studies the participants performed practice trials of the task at hand before estimating their performance (Gilbert, 2015b; Boldt & Gilbert, 2019) or they estimated their performance after the presentation of the to-be-remembered stimuli (Hu et al., 2019; Risko & Dunn, 2015). Therefore, in these studies the participants had some experiences with regard to the upcoming task performance or stimuli which might have affected their metacognitions and in return offloading behavior. If participants have some experience beyond reading the instruction of a task, they might be able to correctly estimate their own performance and then select the proper strategy to solve a working memory task. Metacognitive monitoring in my study might not have been successful due to missing experiences with the task at hand.

To summarize, in the present study I did not observe a relationship of metacognitive beliefs and the offloading of working memory processes on a correlational basis. My study does therefore not support the proposed metacognitive model of cognitive offloading of Risko and

Gilbert (2016). Rather actual working memory abilities than metacognitive beliefs seem to be a strong predictor for the offloading of working memory processes. Nonetheless, I propose to further investigate if metacognitive beliefs causally impact the offloading of working memory processes. An experimental investigation of the influence of metacognitive beliefs on offloading behavior can help to derive further insights into metacognitions as determinants of cognitive offloading.

Declaration regarding collaborative publications/manuscripts

The following chapter (Chapter 3) consists of a manuscript that is currently under revision for publication and was co-authored by Hauke S. Meyerhoff, Stephan Schwan, and Frank Papenmeier. I would like to thank Deniz Geleri, Luna Frauhammer, and Rebekka Hemmrich for their help in conducting this experiment.

Title of paper: *From metacognitive beliefs to strategy selection: Does fake performance feedback influence cognitive offloading?*

Status in publication process: Under revision

3. Study 2

– From metacognitive beliefs to strategy selection: Does fake performance feedback influence cognitive offloading? –

Today, with regard to the pervasive availability of technological aids such as smartphones or tablets, individuals can constantly decide between either externalizing cognitive processes into these aids by, for example, offloading a shopping list onto one's smartphone or relying on their own internal cognitive processing by memorizing the shopping list instead. Technological aids serve as a digital expansion of the individual mind (Clark & Chalmers, 1998) and individuals perceive their external memories as part of themselves (Finley et al., 2018). The determinants of utilizing either internal cognitive processes or external cognitive resources have been the focus of recent research (e.g., Gilbert, 2015a; Gray et al., 2006; Grinschgl, Meyerhoff, & Papenmeier, 2020; Risko & Dunn, 2015; Weis & Wiese, 2018). With the present experiment, we probed whether there is a causal relationship between metacognitive beliefs and offloading behavior by manipulating participants' metacognitive beliefs about their own working memory performance with fake performance feedback.

The externalization of cognitive processes into technological aids is known as *cognitive offloading* (Risko & Gilbert, 2016). Cognitive offloading reduces demands on internal cognitive processing and thus minimizes cognitive effort when performing a task. Furthermore, due to cognitive offloading, individuals can store and handle more information simultaneously than within the restrictions of their internal memory capacity. In other words, cognitive offloading allows for overcoming capacity limitations of internal cognitive processing such as in working memory (Risko & Gilbert, 2016). With regard to working memory, cognitive offloading avoids the internal encoding or actively holding of information that is present in the immediate environment (Wilson, 2002). Instead, individuals can rely on the environment, for example, by using a technological aid to externally store and/or manipulate information and only access the information when needed (Wilson, 2002).

Over the last years, research has identified multiple determinants for offloading behavior (see Risko & Gilbert, 2016, for a review), such as the characteristics of the technological aid and the task at hand. For example, the likelihood of offloading cognitive processes onto a tablet device depends on the responsivity of the device and the smoothness of the control type (Grinschgl et al., 2020). Current research suggests that cognitive offloading is based on cost-benefit considerations (e.g., Gray et al., 2006). When cognitive offloading is associated with low temporal and/or physical costs while interacting with tools, offloading behavior is more pronounced than with high associated costs (e.g., Cary & Carlson, 2001; Gray et al., 2006; Grinschgl et al., 2020). Regarding the task at hand, the information that needs to be processed also influences offloading behavior. For instance, increases in complexity (Schönpflug, 1986), difficulty (Hu et al., 2019), or amount of information (Gilbert, 2015a; Risko & Dunn, 2015) results in an increased offloading behavior.

Recently, researchers interested in cognitive offloading started considering determinants of cognitive offloading related to the user of technological aids, such as users' memory capacity or metacognitive beliefs about their own internal abilities. Individuals offloading behavior is more pronounced, the lower their own internal performance is (Gilbert, 2015b; Risko & Dunn, 2015). Importantly, however, prior research suggests that not only objective memory abilities but also metacognitive beliefs about one's internal memory abilities and one's environment might affect offloading behavior (Arango-Muñoz, 2013). In their review article, Risko and Gilbert (2016) proposed *a metacognitive model of cognitive offloading.* This model states that the decision between internal and external strategies is guided by metacognitive beliefs about one's environment – such as the properties of technological aids – and one's internal memory abilities. Regarding the former, that is, the metacognitive beliefs about one's environment, studies have shown that individuals adapt their offloading behavior according to their beliefs about the benefits of an offloading strategy (Dunn & Risko, 2015) or the reliability of a technological aid (Weis & Wiese, 2018). If individuals expected an offloading strategy to be inefficient for reaching their goal (Dunn & Risko, 2015) or a technological aid to be unreliable (Weis & Wiese, 2018), they offloaded less and relied more on their own internal resources. Regarding the latter – metacognitive beliefs about one's internal abilities – Gilbert (2015b) observed in a prospective memory task that the subjective confidence in one's memory performance predicted offloading behavior, regardless of objective accuracy. Lower confidence in one's memory performance (i.e. less positive metacognitive beliefs about one's memory) was associated with a more extensive use of external reminders, thus more cognitive offloading (Boldt & Gilbert, 2019; Gilbert, 2015b; similar results were obtained by Hu, et al., 2019; Risko & Dunn, 2015). Therefore, individuals might use cognitive offloading as a compensatory strategy if they believe that their internal memory abilities are poor. In a recent experimental study using the same prospective memory task, Gilbert et al. (2020) manipulated the difficulty of practice trials as well as the valence of provided feedback on each trial (positive vs. negative). After performing the practice trials, the participants provided metacognitive performance estimations and then performed the task with the possibility of offloading memory demands. The participants rated their own memory performance to be more accurate when they received positively framed feedback or easier practice trials than when they received negatively framed feedback or more difficult practice trials. This shift in metacognitive beliefs was accompanied by a matching shift in offloading behavior. When a manipulation resulted in less confidence in one's memory abilities, this led to more cognitive offloading. However, all participants showed a bias towards using cognitive offloading extensively, thus metacognitions cannot fully explain offloading behavior in this study (Gilbert et al., 2020). While these findings are a first indication of the connection between metacognitions and cognitive offloading beyond correlational approaches, further investigations are needed to explain their causal relationship as well as the involved processes.

In the present study, we set out to investigate the causal relationship between metacognitive beliefs and offloading behavior by manipulating metacognitive beliefs with fake performance feedback. Performance feedback can influence motivation (Venables & Fairclough, 2009), effort spent on a task (Raaijmakers, Baar, Schaap, Paas, & Van Gog, 2017) as well as goals (Fishbach, Eyal, & Finkenstein, 2010; Ilies & Judge, 2005), even if the feedback is manipulated and therefore false (Ilies & Judge, 2005). With regard to perceptual learning, fake performance feedback has an even higher impact than genuine feedback (Shibata, Yamagishi, Ishii, & Kawato, 2009). Additionally, positive and negative performance feedback can influence beliefs about one's self-efficacy (Nease, Mudgett, & Quiñones, 1999). Individuals often evaluate their own performance in comparison to other individuals, such as those in their peer group (Ilies & Judge, 2005; MacFarland & Miller, 1994). Thus, performance feedback including a social comparison (e.g., "you performed worse/better than your peers") might have a particularly strong effect on metacognitive beliefs. In addition, participants might be less able to judge their own performance in relation to their peers compared to directly estimating their own abilities (without any social comparison). Thus, they might be more vulnerable to fake performance feedback with rather than without social comparisons. For these reasons, we provided the participants of our study with fake performance feedback indicating a below-average or above-average performance compared to their peers (i.e. other students), and we measured metacognitive beliefs with the participants' subjective performance estimations similar to the feedback.

We predicted that fake performance feedback should influence participants' metacognitive beliefs about their own working memory performance. We further hypothesized that the manipulated metacognitive beliefs should transfer into the control of offloading behavior in a working memory task. Therefore, we expected that the participants receiving below-average performance feedback rely more on cognitive offloading while performing a working memory task than those participants receiving above-average performance feedback, with the control group (i.e. no feedback) in between the two. We expected this effect to be due to metacognitive beliefs about the reliability of the internal working memory resources. Whereas the participants receiving below-average feedback should expect their memory to be poor, thus relying more on offloading, those participants receiving above-average feedback should expect their memory to be good, thus relying more on internal processing.

Method

We preregistered the research questions, independent and dependent variables, sample size, exclusion criteria, and the analysis plan of this experiment at the Open Science Framework prior to data collection (https://osf.io/9hpz5).

Participants

We collected valid datasets of 159 participants (113 female, 46 male; age 18 – 32 years, M_{age} = 23.16, SD_{age} = 2.81). According to our preregistered exclusion criteria, we excluded and replaced data of participants when data went missing (3) and when there were errors in data collection (2), participants exceeding threshold values of +/- 3 *SD* for the dependent variables in the Pattern Copy Task (4), participants not performing the Feature Switch Detection Task correctly (i.e. always pressing the same button or performing at chance level; 9) and participants who indicated that they had received other feedback than they actually had at the end of the experiment (i.e. an attention check; 5). We also excluded and replaced one participant who reported difficulties when performing the experiment due to visual impairments. Further, we excluded and replaced 13 participants[2] due to an error in data collection, resulting in missing responses for the paper-and-pencil multifactorial memory questionnaire. The sample size was preregistered and intended to achieve a statistical power of $(1 - \beta) = .80$ with medium effect sizes of $f = 0.25$. The participants were university students and recruited at the University of Tübingen. All participants provided informed consent and received course credits or a financial compensation for their participation. The study was approved by the local ethics committee of the Leibniz-Institut für Wissensmedien.

Apparatus

All computer tasks were performed on 12.3'' Microsoft Surface Pro Tablets (2736 x 1824 pixels) lying flat on the table at a viewing distance of approximately 36 cm. The tablets were controlled by their touch function, and all computer tasks were performed with PsychoPy scripts (Peirce, 2007).

Procedure and Computer Tasks

General procedure. At the beginning of the experiment, we instructed the participants that they will perform multiple different working memory tests and that they might receive feedback about their actual task performance. Thus, the participants were naïve to our manipulations; that is, they neither knew that the performance feedback was actually fake, nor

[2] Please note that exploratorily adding the complete datasets of those participants to the respective analyses changes neither the reported result patterns nor interpretations.

did they know that the fourth test was designed to measure offloading behavior. The participants first completed three successive working memory tasks (Feature Switch Detection Task, Adapted Corsi Blocks Task, Adapted Visual Patterns Test). Each task started with the participants reading the corresponding instructions and then filling out a pre-rating about their expected upcoming performance. After each task, fake performance feedback was presented for the below-average group and above-average group (see below for details on the feedback). With these three tasks, we aimed to achieve a high credibility of the fake performance feedback. As the fourth test, the participants performed our main task – the Pattern Copy Task – measuring spontaneous offloading behavior. The participants were instructed as if this task would just be another common working memory test so that they would transfer the previous fake performance feedback and the associated metacognitive beliefs onto the Pattern Copy Task. After reading the instructions for the Pattern Copy Task, the participants rated their expected upcoming performance. After performing the task, they additionally rated their achieved performance in a post-rating. In addition, they indicated the strategy they used during this task in a follow-up questionnaire. Finally, the participants answered the multifactorial memory questionnaire (MMQ; Troyer & Rich, 2002). All participants were debriefed at the end of the experiment.

Feature Switch Detection Task. We used the Feature Switch Detection Task to measure the participants' actual visual working memory performance (see Meyerhoff & Gehrer, 2017; Wheeler & Traismen, 2002, for similar versions) and additionally provide our participants with their first fake performance feedback. In this task, the participants had to memorize a display with colored boxes that was presented for 150 ms (presentation display, see Figure 4). After a short blank period (900 ms), they then observed another display with only one colored box as the probed object (single-probe display) and had to decide whether the color of this probed object was identical to its previous color in the presentation display or whether there was a change in this feature. The single-probe display was presented until a response was given. The participants gave their response by pressing the corresponding button on the touch display (the color of probed object in the single-probe display was the same or was different compared to the presentation display). The task started with eight practice trials including the presentation display of two colored boxes. After the practice trials, the participants performed three blocks of 40 trials with an increasing set size: Block 1 included four colored boxes; Block 2 included six colored boxes, and Block 3 included eight colored boxes in the presentation display. The colored boxes could have had one of the following colors: red, yellow, green, blue, white, brown, black, magenta and were presented on a gray background. Colors were never repeated within a display, and the colored boxes had a size of 2 x 2 deg of visual angle. In the single-probe display, the probed object either had the same color as in the presentation display (50% of the trials) or it took the color of another object from the presentation display (50% of the trials). The trials were presented in a randomized order within each block. As an index for visual working memory performance, we calculated the proportion of correct responses across all test trials (120 trials in total) per participant.

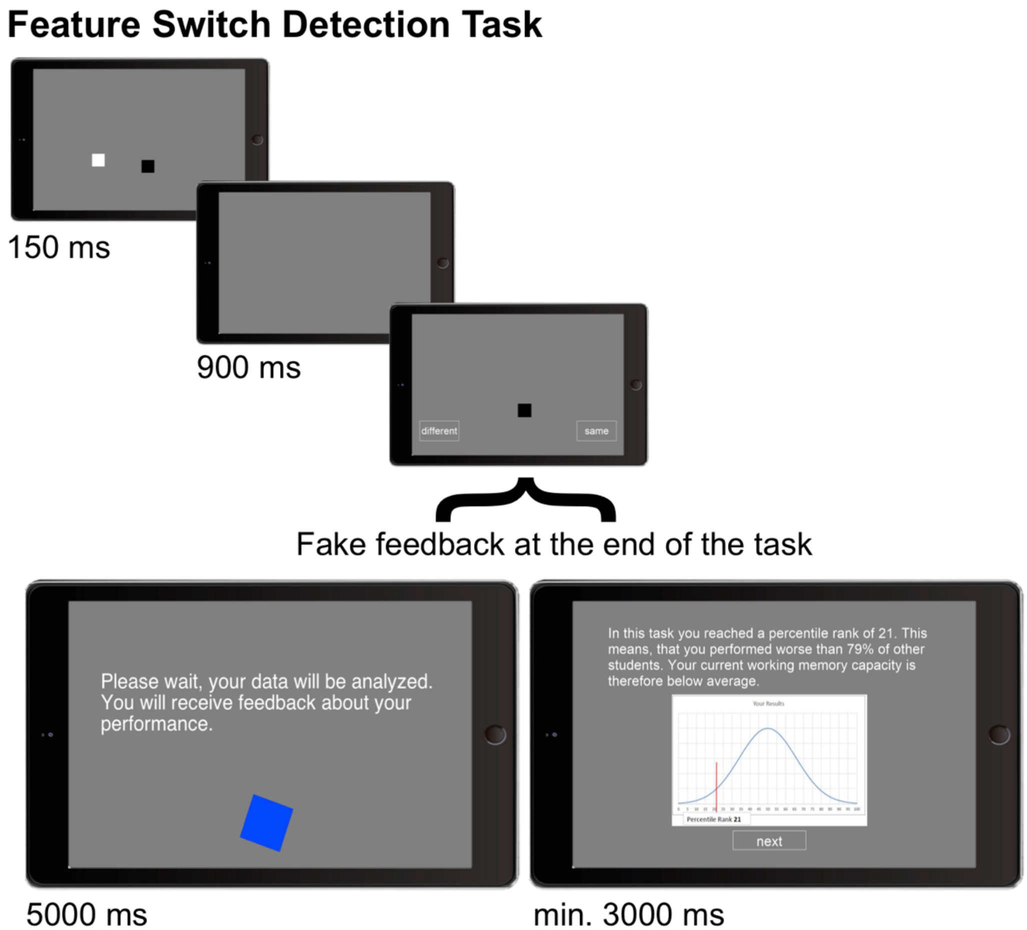

Figure 4. Illustration of the Feature Switch Detection Task, measuring working memory performance. In the Feature Switch Detection Task, the participants had to detect a change in the color of the probed object in a single-probe display. In this example, the color of the probed object did not change; thus, the correct answer is “same” color. After multiple trials with an increasing set size, the participants received fake performance feedback (here illustrated for the below-average group; tablet frame designed by Freepik).

Fake performance feedback. Directly following the task, the participants who received fake performance feedback (below-average group and above-average group) had to wait for 5000 ms in which the computer program (PsychoPy) was pretending to analyze their performance (see

Figure 4). Then, fake performance feedback was presented for at least 3000 ms and until the participants pressed a continue button to exit the feedback. The participants in the control condition did not receive any feedback but instead saw a blue circulating rectangle and the statement “Please wait a moment” (identical to the waiting screen in the other two conditions with exception of the exact statement) on the screen for 8000 ms. They then continued the experiment.

The written feedback gave a fake percentile rank that indicated the performance in the task just performed compared to other students (i.e. their peers) and additionally the meaning of this rank in terms of one’s working memory capacity. More specifically, the feedback after the Feature Switch Detection Task stated the following for the below-average group (in German, here translated into English for illustration):

> “In this task, you reached a percentile rank of 21. This means that you performed worse than 79% of other students. Your current working memory capacity is therefore below average.”

For the above-average group, the following fake performance feedback was given subsequently to the Feature Switch Detection Task:

> “In this task you reached a percentile rank of 79. This means that you performed better than 79% of other students. Your current working memory capacity is therefore above average.”

In addition, the percentile rank was also visually displayed in a normal distribution. The fake performance feedback for the below-average and above-average groups was consistent across the three tasks for which fake performance feedback was provided. Only the reported values slightly varied. Following the Adapted Corsi Blocks Task, the fake performance feedback for the below-average group was a percentile rank of 23 and for the above-average group a percentile rank of 77. Following the Adapted Visual Patterns Test, the fake performance feedback for the below-average group was a percentile rank of 20, whereas for the above-average group, it was a percentile rank of 80.

Adapted Corsi Blocks Task. We presented an adapted Corsi Blocks Task (for original version see Della Sala et al., 1999) in order to provide further fake performance feedback. In this task, the participants were presented with a 5 x 5 grid of empty squares (2.52 x 2.52 deg) on a white display. In a presentation phase, single squares of this grid turned yellow in a specific order (one by one, in a 700 ms rhythm). After the presentation phase and a short blank phase (500 ms), the participants again observed a sequence of single squares turning yellow. They then had to decide whether the second sequence was identical to the first one or not. On 50% of the trials, the sequence was identical; on the other 50% of trials, the sequence was different (one single yellow square was presented in a different position on the grid). The participants performed 36 trials, with the sequence length increasing from four objects turning yellow (12 trials), to six objects turning yellow (12 trials), and finally eight objects turning yellow (12 trials). Subsequently, fake performance feedback was presented according to the participant's feedback group. We did not analyze actual performance within this task as it only served to provide fake performance feedback.

Adapted Visual Patterns Test. This task was also modified from its original version (Della Sala et al., 1999) to provide the participants with fake performance feedback. In this task, the participants had to detect a change between two displays. The displays included a 5 x 5 grid of empty squares (2.52 x 2.52 deg). Some of these squares were filled with colors in a presentation phase (250 ms). After a short blank phase (1000 ms), the participants observed a second display that was either identical (50% of trials) or the position of one colored square changed (50% of trials; in a randomized order). Thus, the participants had to decide whether the displays were identical or not. In a total of 36 trials, the set size increased, starting with 12 trials with six colored squares each, followed by 12 trials with eight colored squares each, and 12 trials with 10 colored squares each. At the end of this task, the participants received the third and thus last fake performance feedback according to their feedback group. We again did not analyze actual performance within this task.

Pattern Copy Task. The Pattern Copy Task is a working memory task that was designed to measure spontaneous offloading behavior (e.g., Ballard et al., 1992; Ballard et al., 1995; Gray et al., 2006). The participants were told that they will perform another working memory test that measures their visual working memory capacity (i.e. they did not know about our focus on cognitive offloading). Within this task, the participants had to copy a color pattern from a model window into an empty workspace window (see Figure 5). The model window comprised a 5 x 5 grid of empty squares (2.52 x 2.52 deg each). Twelve of these squares were randomly filled with distinct colors (blue, orange, red, cyan, green, dark green, yellow, bisque, sienna, purple, pink, gray; no color was repeated). Thus, the model window presented a color pattern on the left side of the screen that the participants had to reproduce in the workspace window on the right side of the screen. The workspace window presented the same 5 x 5 grid of empty squares, and additionally beneath this workspace window, a resource window was displayed. The resource window contained all the colored boxes to be dragged and dropped into the workspace window. Importantly, all windows were covered by gray masks and only either the model window on the left side of the screen or the workspace and resource window on the right side of the screen could be opened. The model window opened by moving a slider to the left, and the workspace as well as resource window opened by clicking onto a bar next to it. The participants could switch between the windows as often as they wanted. After correctly rebuilding the color pattern in the workspace window, the participants could proceed to the next trial by clicking an “End Trial”-

button. If the pattern was not rebuilt correctly, they were requested to keep editing it.[3] The participants performed 20 trials of this task, preceded by five practice trials. The trial order and color patterns allocated to the trials was randomized to the extent that one participant of each feedback group (below-average, above-average and control group) received the exactly same trial order and color patterns in order to eliminate potential effects of different stimuli. We measured the offloading of working memory processes with three variables: the number of openings of the model window, the number of correctly copied items after the very first opening of the model window, and the duration of the very first opening of the model window. A higher number of openings indicated more cognitive offloading, whereas more initially correctly copied items and a higher initial encoding duration indicated less cognitive offloading and more memorized information. This task measured spontaneous offloading behavior; thus, the participants were not informed about different strategies (i.e. relying more on cognitive offloading or one's internal memory) that they might use to solve this task. Instead, the participants had to decide spontaneously which strategy to apply (see also Ballard et al., 1995). This spontaneous offloading behavior resembles the cognitive offloading as performed during daily real-life situations in which individuals usually are also not instructed about specific strategies.

[3] Please note that the participants rarely pressed the "End Trial"-button whenever the pattern was not correctly rebuilt. Across the 20 trials of the Pattern Copy Task, we observed the following means and standard deviations for the number of times the "End Trial"-button was pressed prematurely: below-average group: $M = 0.29$ ($SD = 0.36$); control group: $M = 0.19$ ($SD = 0.15$); above-average group: $M = 0.20$ ($SD = 0.14$). Excluding the trials in which participants pressed the "End Trial"-button prematurely did not change our findings.

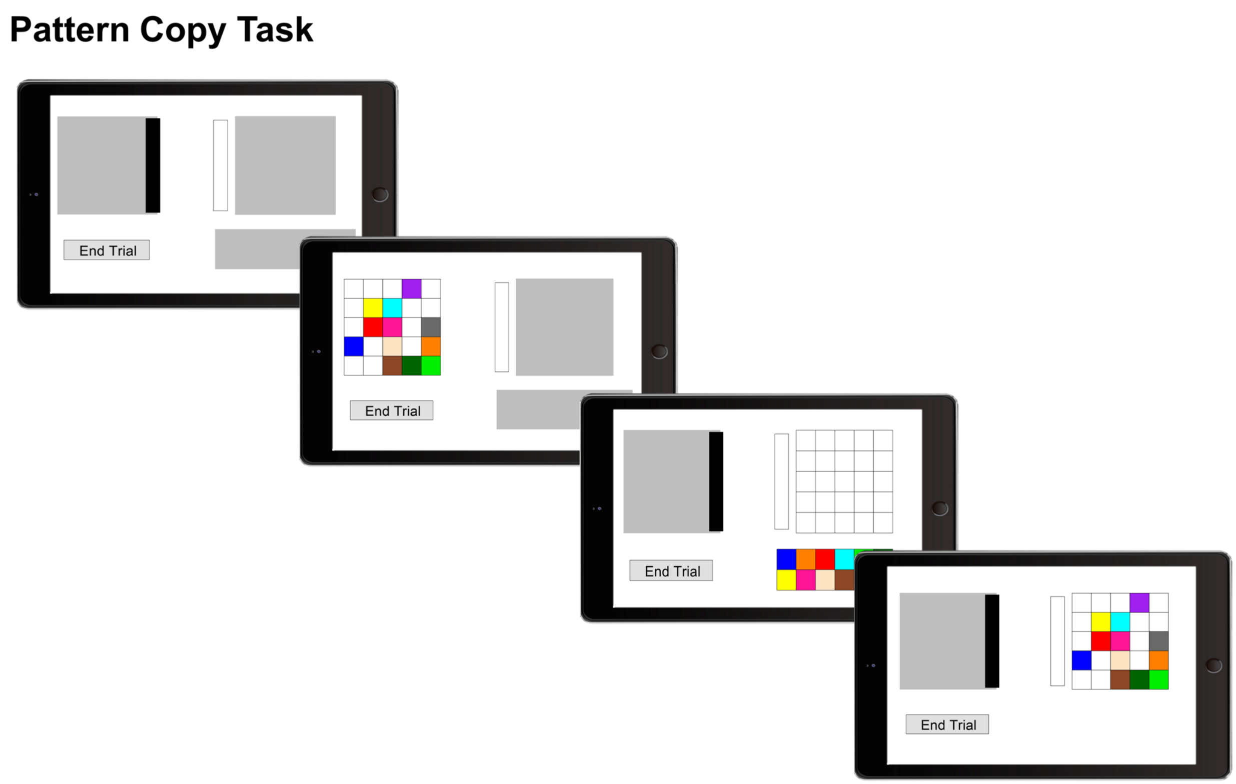

Figure 5. Illustration of the Pattern Copy Task measuring offloading behavior. The participants had to copy a color pattern from a model window (left side) to a workspace window (right side) by dragging colored boxes from an additional resource window (lower right side). The windows were never visible at the same time, but the participants could switch between them as often as they wanted. They could proceed to the next trial once they had correctly rebuilt the pattern. (Tablet frame designed by Freepik).

Paper and Pencil Tasks

In addition to the computer tasks, we also asked the participants to answer some supplementary measures on paper.

Subjective performance ratings. Before performing any computer task, we asked the participants to rate their upcoming performance in comparison to other students. Therefore, they read the instruction of the corresponding task first and then indicated their performance on a 0 to

100 percentile rank scale. In total, there were four of these pre-ratings (before the Feature Switch Detection Task, the Adapted Corsi Blocks Task, the Adapted Visual Patterns Test and the Pattern Copy Task). For the final Pattern Copy Task, we additionally collected one post-rating. After the completion of this task, the participants rated their actual performance within the Pattern Copy Task on the same scale from percentile 0 to 100.

Offloading-Strategies. After performing the Pattern Copy Task and filling out the post-rating, the participants were asked about the strategies they used while performing this task. Therefore, we presented the following question and answers to the participants: "What strategy did you use to complete the last task?" with the response options: "I tried to memorize a lot at once instead of having to take a look more often." or "I tried to take a look more often instead of memorizing a lot at once." (presented in German; here translated into English for illustration). Thus, the participants could choose between a strategy that implies a more memory intense-strategy (i.e. memorizing more information and looking up the required information less often, "internal strategy") or more cognitive offloading (i.e. looking up the required information more often and memorizing less information, "offloading strategy").

Multifactorial Memory Questionnaire. At the end of the entire experiment, the participants filled out the MMQ (Troyer & Rich, 2002; adapted and translated by us). This adapted version included statements about meta-memory contentment (18 statements) and omitted other parts of the original version. The statements that we included dealt with the satisfaction with and confidence in someone's memory abilities, such as "I am generally pleased with my memory ability". The participants rated how strongly they agreed with these statements on a 5-point Likert scale (from "strongly agree" to "strongly disagree"). We aimed to measure participants' subjective beliefs about their general memory abilities. Thus, we averaged all 18 ratings to receive an index of subjective beliefs about their general memory abilities (higher values indicate more positive beliefs). Our adapted and translated questionnaire provided a high internal consistency with a Cronbach's alpha of .93.

Design

Our experiment followed a between-subjects design with three feedback groups (below-average vs. above-average vs. control). In the below-average group, the participants received fake performance feedback indicating below average working memory capacity. In the above-average group, the participants received fake performance feedback indicating above average working memory capacity. The control group did not receive any feedback at all.

Results

Subjective Performance Ratings

To investigate whether the participants changed their metacognitive beliefs according to the provided fake performance feedback, we performed a preregistered mixed 2 x 3 ANOVA with the within factor "time of pre-rating" (first pre-rating before receiving any feedback vs. fourth pre-rating after receiving feedback for three times) and the between factor "feedback group" (below-average vs. above-average vs. control). We were especially interested in the fourth pre-rating as it was provided immediately before the main task (Pattern Copy Task) measuring cognitive offloading. We observed a main effect of the factor "feedback group", $F(2, 156) = 19.74$, $p < .001$, $\eta^2 = .12$, as well as a main effect of the factor "time of pre-rating", $F(1, 156) = 22.67$, $p < .001$, $\eta^2 = .04$. Most importantly, we also found a significant interaction between these factors, $F(2, 156) = 20.09$, $p < .001$, $\eta^2 = .07$. Post-hoc *t*-Tests for independent samples between each feedback group showed that there were no group differences in the first pre-rating, all ts(104) <= 1.68, all ps >= .094, all ds <= 0.33, whereas all groups differed from each other in the fourth pre-rating, all $|ts(104)| >= 3.21$, all $ps <= .001$, all $|ds| >= 0.62$ (see Figure 6). Thus, as expected, at the very first pre-rating before receiving any fake performance feedback, the participants did not differ in their metacognitive beliefs about their upcoming performance, but after receiving fake performance feedback three times, the below-average group indicated the lowest performance, whereas the above-average group indicated the highest performance, with the control group in the middle.[4]

[4] An exploratory mixed 5 x 3 ANOVA including all four pre-ratings as well as the post-rating after performing the Pattern Copy Task and the three feedback groups revealed the same pattern of results for the dependent variable "subjective performance ratings", all $F(2, 156)s >= 10.29$, all $ps < .001$, all $\eta^2s >= .03$. There were no group differences at the very first rating (Pre 1), but all groups differed in their performance estimations already after receiving fake performance feedback once (i.e. group differences in Pre 2, Pre 3, Pre 4; all $|ts(104)| >= 3.21$, all $ps <= .001$, all $|ds| >= 0.62$) and even after performing the Pattern Copy Task (i.e. post-rating; all $|ts(104)| >= 3.34$, all $ps <= .001$, all $|ds| >= 0.65$). Participants in the below-average group rated their performance lower than participants in the above-average group with the control group in the middle.

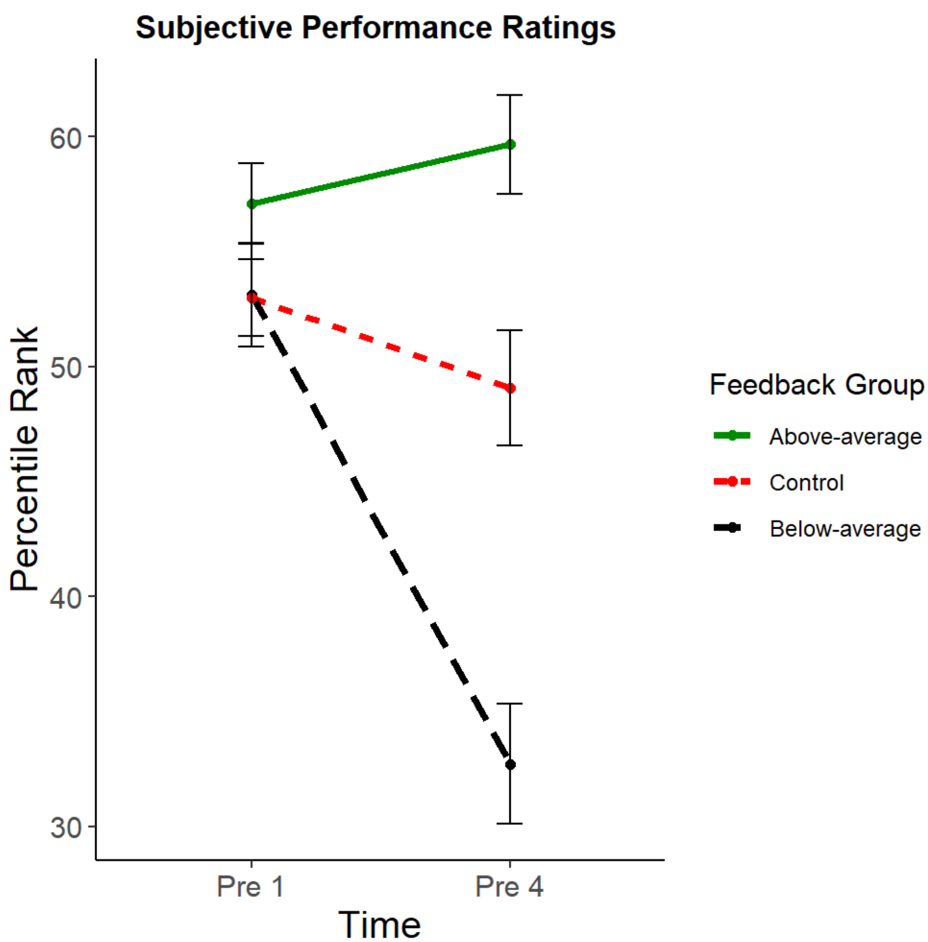

Figure 6. Subjective performance ratings prior to receiving fake performance feedback (Pre 1) and after receiving multiple fake performance feedback (Pre 4; with standard errors of the mean as error bars). We observed no group differences at the first pre-rating before receiving fake performance feedback and significant differences between all feedback groups at the fourth pre-rating after receiving fake performance feedback and before performing the Pattern Copy Task.

Cognitive Offloading

We performed preregistered one-way ANOVAs for the between factor “feedback group” (below-average vs. above-average vs. control) and each of the three dependent offloading variables of the Pattern Copy Task. The three feedback groups did not differ significantly in the number of times the model window was opened, $F(2, 156) = 1.04$, $p = .354$, $\eta^2 = .01$, the number of initially correctly copied items, $F(2, 156) < 0.01$, $p = .998$, $\eta^2 < .01$, and the initial encoding duration, $F(2, 156) = 0.97$, $p = .383$, $\eta^2 = .01$ (see Table 5). Thus, our fake feedback manipulation did not alter offloading behavior in the Pattern Copy Task. For exploratory purposes, we also analyzed the trial duration within the Pattern Copy Task as an indicator of task performance. The three feedback groups did not differ in the trial duration, $F(2, 156) = 0.73$, $p = .486$, $\eta^2 = .01$ (see Table 5).

Table 5. *Means and Standard Deviations of Dependent Variables in Cognitive Offloading as Well as Trial Duration in the Pattern Copy Task and Working Memory Performance in the Feature Switch Detection Task*

	Below-average Group	**Control Group**	**Above-average Group**
	M (SD)	*M (SD)*	*M (SD)*
Cognitive Offloading			
Openings of the Model Window	5.39 (1.08)	5.14 (1.02)	5.09 (1.25)
Initially Correctly Copied Items	3.26 (0.61)	3.26 (0.74)	3.27 (0.71)
Initial Encoding Duration (sec)	7.21 (3.52)	7.17 (4.53)	6.33 (2.83)
Trial Duration (sec)	43.45 (8.49)	41.42 (10.10)	41.73 (9.38)
Working Memory Performance	0.74 (0.07)	0.73 (0.07)	0.73 (0.09)

Offloading-Strategies

Following the Pattern Copy Task, the participants stated which strategy they had preferred during this task. They could either choose a strategy that indicated more cognitive offloading ("offloading strategy") or a strategy that indicated more internal cognitive processing ("internal strategy"). The participants that indicated both strategies were excluded from this exploratory analysis (remaining participants: $N = 146$, see Table 6). We used a logistic regression and the Anova-function from the car package (Fox & Weisberg, 2019) in order to analyze the differences in the selected strategies across the three feedback groups. There was a significant main effect of feedback group on the selected strategies, $X^2(2) = 10.39$, $p = .005$, $d = 0.55$, indicating that the fake performance feedback had affected the participants' choice of which strategy they thought they had used during the Pattern Copy Task. We used reduced logistic regressions, including only two feedback groups each in order to calculate pairwise comparisons. This comparison revealed that the participants from the below-average condition indicated that they had preferred an offloading strategy over an internal strategy to a larger extent than the participants from the above-average condition, $X^2(1) = 10.39$, $p = .001$, $d = 0.69$. Thus, despite not having observed an objective change in offloading behavior in our Pattern Copy Task, the participants on average reported that they had shifted their strategy in the direction that we had predicted. Further, despite the fact that the numerical frequencies indicate that the control group was right between the below-average condition and above-average condition, those paired comparisons did not reach significance, $X^2(1) = 2.90$, $p = .088$, $d = 0.35$, and $X^2(1) = 2.34$, $p = .126$, $d = 0.31$, respectively.

Additionally, we calculated exploratory point-biserial correlations between strategy selection and actual offloading behavior (see Table 7). Strategy selection and offloading were not significantly correlated in the below-average group. In the above-average group, they were also no significant correlations with the exception of the initial encoding duration. In the control group, however, strategy selection did correlate significantly with cognitive offloading, all |*r*s(46)| >= .39, all *p*s <= .005. Overall, this analysis indicates that self-reported strategies matched actual performance only in the control group, but not in the groups with experimental manipulations of metacognitive beliefs about one's own memory performance.

Table 6. *Participants per Group That Indicated Using Either an "Offloading Strategy" or an "Internal Strategy" in the Pattern Copy Task*

	Below-average Group	**Control Group**	**Above-average Group**
	N	*N*	*N*
Offloading Strategy	36	29	23
Internal Strategy	11	19	28

Table 7. *Point-Biserial Correlations Between Reported Strategy Selection (0 = Internal Strategy, 1 = Offloading Strategy) and Actual Offloading Behavior*

	Below-average Group	**Control Group**	**Above-average Group**
	r(45)	*r*(46)	*r*(49)
Openings of the Model Window	.07	.40**	.01
Initially Correctly Copied Items	-.19	-.39**	-.09
Initial Encoding Duration (sec)	.06	-.53***	-.31*

Note: * $p < .05$, ** $p < .01$, *** $p < .001$

MMQ

An exploratory one-way ANOVA revealed significant group differences in beliefs about one's general memory abilities at the end of the experiment, $F(2, 156) = 7.08$, $p = .001$, $\eta^2 = .08$. Additional *t*-Tests for independent samples showed that the below-average group rated their general memory abilities lower than the above-average group, $t(104) = 2.98$, $p = .003$, $d = 0.58$, and the control group, $t(104) = 3.19$, $p = .002$, $d = 0.62$. We observed no significant difference between the above-average group and the control group, $t(104) = 0.25$, $p = .801$, $d = 0.05$ (see Figure 7). Thus, our fake performance feedback manipulation altered the participants' beliefs about their general memory abilities in the direction of the feedback provided, particularly for the below-average group.

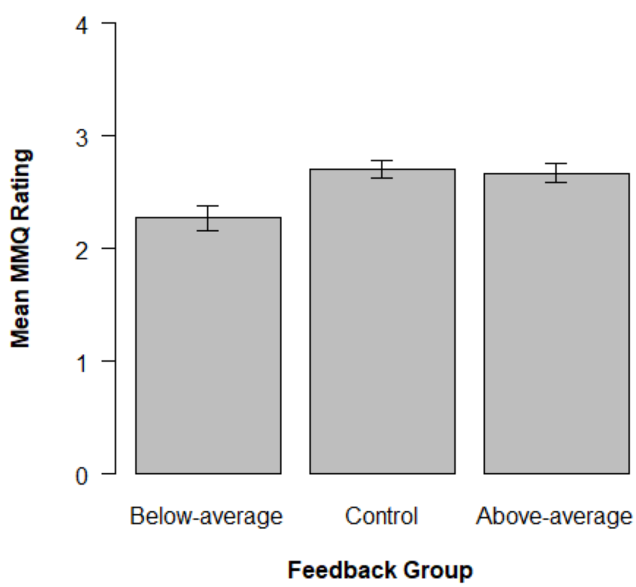

Figure 7. Ratings of beliefs about one's general memory abilities measured with the MMQ at the end of the experiment (averaged for each group; with standard errors of the mean as error bars). Higher values indicate more positive beliefs about one's general memory abilities. The below-average group indicated worse general memory abilities than the other two groups.

Working Memory Capacity

To exclude that any group effects are due to differences in actual working memory abilities, we used the Feature Switch Detection Task to measure visual working memory performance for color-location bindings. A preregistered one-way ANOVA indicated that there were no significant group differences in this working memory performance measure, $F(2, 156) = 0.07$, $p = .929$, $\eta^2 < .01$ (see Table 5), just as one would expect given the randomized assignment of the participants to the experimental conditions.

Discussion

In the present study, we investigated the causal impact of metacognitive beliefs about one's working memory on cognitive offloading in a working memory task. Metacognitive beliefs are supposed to influence one's decision for using specific strategies when performing a task based on metacognitive monitoring and controlling. Thus, metacognitive beliefs should affect the use of technological aids (and likewise cognitive offloading) or one's internal working memory resources. In order to experimentally test the determining role of metacognitive beliefs when offloading working memory processes, we used fake performance feedback. Our fake performance feedback successfully manipulated metacognitive beliefs about one's working memory. Before receiving any feedback, the three feedback groups did not differ in their pre-rating about their upcoming working memory performance, but after receiving fake performance feedback, they differed accordingly. The participants receiving below-average performance feedback rated their working memory performance the lowest, and those participants receiving above-average performance feedback rated their working memory performance the highest, with the control group that did not receive any feedback in between. Remarkably, the effect of fake performance feedback was so strong that it even spilled over to general beliefs about one's memory abilities (measured by the MMQ) at the end of the experiment. The participants in the below-average group estimated their general memory abilities lower than the other two groups. Thus, especially below-average performance feedback affected metacognitive beliefs broadly and persistently. Although our manipulation of metacognitive beliefs altered the participants' subjective working memory ratings, it had clearly no impact on offloading behavior within the Pattern Copy Task. Within this task, participants could either rely more on a technological aid by looking up information more often (i.e. more cognitive offloading) or rely more on their own internal memory by looking up the information less often (i.e. less cognitive offloading). We observed that spontaneous offloading behavior within the Pattern Copy Task was nearly identical across all feedback groups.

Previous research suggests that metacognitive beliefs are negatively correlated with offloading behavior (Boldt & Gilbert, 2019; Gilbert, 2015b; Hu, et al., 2019; Risko & Dunn, 2015). For instance, in studies applying a prospective memory paradigm (Gilbert, 2015b; see also Boldt & Gilbert, 2019; Gilbert et al., 2020), the participants had to drag circles with ascending numbers one after another to the bottom of the screen. At the beginning of a trial, the participants were instructed that some special circles (e.g., the circle with the number 3) had to be dragged to another side of the screen (e.g., the left side) when it was their turn. These special circles induced intentions that the participants needed to fulfill later on. After performing practice trials, the participants were asked to rate their upcoming performance (0 to 100 % of special circles dragged to the correct location). The participants then performed several trials of the task without the option to offload, followed by several trials that allowed cognitive offloading. In these latter trials the participants could offload the intentions by placing the special circles close to the correct side of the screen already at the beginning of a trial. More positive beliefs about one's unaided memory performance were associated with less cognitive offloading (Boldt & Gilbert, 2019; Gilbert, 2015b; see also Hu et al., 2019; Risko & Dunn, 2015, for similar results). While these correlational findings suggest a relationship between metacognitive beliefs and offloading behavior, we did not observe a matching impact of metacognitive beliefs on cognitive offloading in the present experimental study. To resolve these seemingly conflicting results, we suggest that differences in the measurement of metacognitions (i.e. measuring metacognitive beliefs vs. metacognitive experiences) across studies might explain the diverging results.

In the present study, we measured metacognitive beliefs after providing the participants with the task instruction but – importantly – *before* they gained any actual experience in performing the task. Therefore, *metacognitive beliefs* within our study were mainly driven by general beliefs about one's working memory based on fake performance feedback in other tasks. In contrast, previous research reporting significant effects of metacognitions on offloading behavior collected metacognitive performance estimations *after* participants performed practice trials (Boldt & Gilbert, 2019; Gilbert, 2015b) or the presentation of the relevant stimuli (Hu, et al., 2019; Risko & Dunn, 2015). Thus, metacognitions measured in the previous studies rather reflect *metacognitive experiences* that are directly related to ongoing metacognitive processing and that refer to what individuals experience while performing a task (Efklides, 2008). This latter design was also used in a recent study showing that the manipulated valence of feedback on task trials influenced metacognitions and in return offloading behavior (Gilbert et al., 2020). Therefore, we suggest that it might actually be metacognitive experiences (as measured by the previous studies) rather than metacognitive beliefs (as measured in our study) that drive offloading behavior.

The suggestion that metacognitive experiences rather than metacognitive beliefs alter offloading behavior fits in well with research showing that actual offloading behavior is determined by the properties of the task at hand and thus probably metacognitive experiences. In like manner, cognitive offloading is known to be driven by external factors such as tool design (Grinschgl et al., 2020), costs when interacting with external tools (e.g., Cary & Carlson, 2001; Gray et al., 2006; Grinschgl et al., 2020), or characteristics of processed information (Gilbert, 2015a; Hu et al., 2019; Risko & Dunn, 2015; Schönpflug, 1986). Such external factors are likely to influence metacognitive experiences while performing a task and in turn influence offloading behavior. Within this context, the new finding of our study is that metacognitive beliefs in contrast to metacognitive experiences had no influence on offloading behavior – at least not within the Pattern Copy Task.

Interestingly, we observed an influence of fake performance feedback on subjective judgements regarding the offloading strategy in the Pattern Copy Task. The participants in the below-average group were more likely to report an offloading strategy over an internal strategy than the participants from the above-average group, although their actual offloading behavior was nearly identical. The distinction between metacognitive beliefs and metacognitive experiences also provides a way to resolve the apparent contradiction between perceived and actual strategy use. Whereas metacognitive experiences could be the main determinant of actual offloading behavior in the Pattern Copy Task, participants might rather consider their metacognitive beliefs when giving subjective judgements on their behavior. For instance, negative beliefs about one's performance might lead participants to judge their behavior as offloading more (although they actually did not offload more) than positive beliefs about one's performance. Thus, based on metacognitive beliefs, the same actual behavior might be interpreted differently by the participants. This assumption was further supported by exploratory correlations showing that the reported strategy selection did not correlate with the actual offloading behavior in the below-average group as well as in the above-average group across most offloading-variables.

Interestingly, however, in the control group we did indeed observe such a correlation; that is, participants that reported to have used an offloading strategy in fact also offloaded more within the Pattern Copy Task. Thus, without a manipulation of metacognitive beliefs with fake performance feedback, participants could correctly judge their own performance.

When relating the findings of our present study to previous research, it is also important to consider the differences between the offloading tasks applied. For instance, in a prospective memory task that has established a correlation between metacognitions and cognitive offloading (Boldt & Gilbert, 2019; Gilbert, 2015b), the participants offloaded future intentions, whereas in the Pattern Copy Task the participants offloaded by looking up relevant information. These two kinds of offloading behavior might be different per se, thus also be guided by different determinants. It is possible that fake performance feedback and in return metacognitive beliefs would indeed drive the offloading of intentions in a prospective memory task, but not offloading behavior in the Pattern Copy Task. We can only speculate about the different processes involved in these offloading paradigms as no study has directly compared them. However, one important difference might be the involved timing when offloading memory processes. Whereas in studies using the prospective memory task (Boldt & Gilbert, 2019; Gilbert, 2015b; Gilbert et al., 2020), the participants offloaded future intentions (i.e. the information is offloaded for remembering it later on), in the Pattern Copy Task the participants offloaded information for instantaneous use (i.e. looking up information more often for the ongoing copy task). Thus, offloading of future intentions might be related to planning before actual task performance, while offloading in the Pattern Copy Task might be related to ongoing processes throughout the task.[5] Metacognitive beliefs could possibly play a greater role for planning before action (thus affecting the offloading of intentions) rather than for offloading during ongoing task processing. Further research is

[5] We would like to thank an anonymous reviewer for suggesting this idea.

needed to investigate the different as well as shared processes involved in cognitive offloading across various paradigms.

Another difference between previous studies investigating metacognitions as determinant of cognitive offloading (e.g., Gilbert, 2015b) and the present study is the specific framing of participants' performance estimations. While in previous studies the participants estimated their own performance based on how accurate they think their own performance is (0 to 100% accuracy; Boldt & Gilbert, 2019; Gilbert, 2015b; Gilbert et al., 2020; Risko & Dunn, 2015), in our experiment they estimated their performance in comparison to other students via a percentile rank. This latter estimation in our study was in line with the provided fake performance feedback that was designed to have a strong impact due to social comparisons (MacFarland & Miller, 1994). One could argue, that this fake performance feedback and in return metacognitive beliefs measured by a comparison indicator did not impact offloading behavior due to its specific framing. It might be possible that cognitive offloading was guided rather by metacognitive beliefs about one's performance estimations without any comparison (i.e. the participants might adopt their offloading behavior based in their confidence in their own memory, independent of its relation to other individuals). However, in our study we also measured metacognitive beliefs with the MMQ that did not include any estimations compared to other individuals and - importantly - our manipulation also affected the metacognitive beliefs as measured in this questionnaire following below-average performance feedback. We thus consider it unlikely that the specific framing of the fake performance feedback as well as performance estimations was a key factor in explaining differences in results between our present study and previous research on cognitive offloading.

The participants in the below-average group estimated their general memory abilities lower than the other two feedback groups. Thus, it seems that below-average performance feedback has a particularly strong influence on metacognitive beliefs and self-perception. In a similar vein, Davis and Brock (1975) showed that below-average performance feedback influences the participants' self-awareness compared to no feedback or above-average feedback, while the latter two conditions did not differ from each other. However, it might not only be below-average feedback per se that strongly influences metacognitive beliefs. Another possibility could be that below-average feedback induces a large deviation from one's primary beliefs before receiving feedback. For instance, one might think that his or her performance is slightly above average. In this case, receiving above-average feedback suggesting a percentile rank of 79% might be less unexpected and thus have less impact than below-average feedback suggesting a percentile rank of 21%, which might largely deviate from one's primary beliefs. Nonetheless, our findings suggest that below-average performance feedback is particularly suited to experimentally manipulate the participants' self-perception - an important insight for future experiments.

Conclusion

Out study aimed to experimentally test the causal impact of metacognitive beliefs about one's working memory performance on the offloading of working memory processes with modern technological tools. While fake performance feedback successfully manipulated metacognitive beliefs regarding the participants' performance on the tasks at hand, as well as their memory abilities in general, we did not observe a change in actual offloading behavior. We propose that that this putative discrepancy can be resolved by taking the distinction between metacognitive beliefs and metacognitive experiences into account. Whereas participants' subjective ratings might be largely influenced by their metacognitive beliefs, actual offloading behavior might largely depend on metacognitive experiences and properties of the task at hand –

at least within the Pattern Copy Task. Thus, performing future research investigating the influence of metacognitive beliefs and experiences on both strategy selection before starting a task and while performing a task across different offloading paradigms will help to generate a more complex and broadly applicable metacognitive model of cognitive offloading.

Declaration regarding collaborative publications/manuscripts

The following chapter (Chapter 4) consists of a manuscript that is currently in preparation for submission and was co-authored by Frank Papenmeier and Hauke S. Meyerhoff. Experiment 2 of this manuscript was conducted as part of the bachelor thesis of Ines Röhrle and was also part of the WCT-Project of Hauke S. Meyerhoff and Frank Papenmeier. I would like to thank Jiahui An, Maria Badanova, Luna Frauhammer, Deniz Geleri, Rebekka Hemmrich, and Ines Röhrle for their help in conducting the experiments.

Title of paper: *Consequences of cognitive offloading: Boosting performance but diminishing memory*

Status in publication process: In preparation.

4. Study 3

– Consequences of cognitive offloading: Boosting performance but diminishing memory –

Already 2.5 million years ago, ancestors of Homo Sapiens used tools in order to improve performance on particular tasks (e.g., using bones for butchery; Ambrose, 2001). Since then, tools have been developed further and modern technologies not only support physical actions but also allow for the externalization of cognitive processes (see Osiurak et al., 2018). Tablets and smartphones are examples of such modern technical tools, and they have become ubiquitous in everyday life (Greenhow, Robelia, & Hughes, 2009). Even though most of the tools support immediate performance, such as performing a task faster and/or with fewer errors, potential mental depletion following their extensive use has been discussed for cognitive tools (e.g., impaired scene recognition after using navigation systems; Fenech et al., 2010). In the present set of experiments, we studied memory as one of the most fundamental cognitive processes. Specifically, we investigated a trade-off between immediate performance and subsequent mental representations due to cognitive offloading.

Cognitive Offloading

Using tools for externalizing cognitive processes is typically referred to as *cognitive offloading* (Risko & Gilbert, 2016). With regard to working memory, the act of cognitive offloading releases resources which otherwise would be necessary to actively hold information in short-term representations. Instead, the corresponding information is externalized into technical tools such as mobile touch devices (Wilson, 2002). Whether humans tend to offload cognitive processes such as memory depends on cost-benefit evaluations of internal processing versus externalization. Raising the costs of externalizations (e.g., by adding additional physical or temporal demands) increases the use of internal strategies such as memory-based processing, whereas lowering the costs of externalizations increases the use of technical tools (e.g., Cary & Carlson, 2001; Gray & Fu, 2004; Gray, et al., 2006; Morgan & Patrick, 2013; O'Hara & Payne, 1998; Schönpflug, 1986).

A typical working memory task used to study the externalization of memory is the Pattern Copy Task (called Blocks World Task in previous work; Ballard et al., 1992; 1995). In this task, the participants replicate a color pattern displayed in a model window on one side of the screen in an empty workspace window on the other side of the screen. In most versions of the task, the model window and workspace window are not visible at the same time, but instead one window is covered by a gray mask whenever the other one is uncovered (e.g., Fu & Gray, 2000; Gray et al., 2006). This design allows participants to decide whether they prefer to rely on internal memorization (indicated by fewer switches between the two windows) or to rely on externalizations of the memory processes (indicated by more switches between the two windows). The participants' decision between internal memorization and externalization depends on subjective cost-benefit considerations. With regard to these considerations, the work of Fu and Gray (2000; see also e.g., Gray et al., 2006; Grinschgl et al., 2020; Patrick et al., 2015; Waldron et al., 2011) has shown that increasing access costs by adding temporal delays for each inspection of the model window results in a shift from offloading strategies to more memory-based strategies. Thus, higher temporal costs reduce offloading behavior. In the present research, we use this robust and consistent finding to experimentally investigate offloading behavior and its immediate impact on performance as well as subsequent memory.

Consequences of Cognitive Offloading

Conceptually, externalization of cognitive processes into a technical tool could be considered an extended mind as externalizations spread cognitive processes beyond the boundaries of the individual mind (Clark & Chalmers, 1998). Empirically, such externalizations have been shown to improve problem-solving accuracy as well as speed (Kirsh & Maglio, 1994). Such beneficial effects on immediate task performance in terms of speed and/or accuracy have been observed across a large variety of tasks (e.g., arithmetic tasks, see Carlson et al., 2007; Goldin-Meadow et al., 2001; or reading, see Risko et al., 2014). Besides these described effects *with* technology (i.e. performing beyond internal cognitive constraints; Salomon, 1990), little is known about the effects *of* technology (i.e. the cognitive consequences of interactions with technology; Salomon, 1990; Salomon & Perkins, 2005).

On the one hand, offloading irrelevant information into technical tools improves cognitive performance for subsequent, unrelated tasks (Runge et al., 2019) as well as memory for unrelated information (Storm & Stone, 2015). On the other hand, however, a common concern states that frequent externalization of internal cognitive processes leads to an impoverishment of the corresponding internal abilities. This concern has received empirical support from findings on spatial memory (e.g., Fenech et al., 2010; Gardony et al., 2015), problem solving (Moritz et al., 2020; O’Hara & Payne, 1998; van Nimwegen & van Oostendorp, 2009), as well as the recall of information (Eskritt & Ma, 2014; Kelly & Risko, 2019a; Pyke & LeFevre, 2011; Sparrow et al., 2011). For instance, O’Hara and Payne (1998) observed that problem solving was less successful in a transfer phase following an increasing amount of interactions with a technical tool relative to using internal mental processes. Moreover, Kelly and Risko (2019a) recently studied how relying on external representations affects memory accuracy for the offloaded information. Despite identical stimulus encoding, the participants of this study remembered word lists less accurately when they thought they would have access to external representations than when they thought they would have to rely on their internal memory.

Critically, in these lines of research, the participants typically could not choose how to perform the task while encoding task-relevant information (e.g., Eskritt & Ma, 2014; Kelly & Risko, 2019a; Sparrow et al., 2011). This is different for the Pattern Copy Task, in which the participants can freely adapt their offloading behavior and thus choose their preferred strategy. Nevertheless, research exploring the Pattern Copy Task points toward a similar trade-off between positive and negative effects of cognitive offloading (Morgan et al., 2009; 2013; Waldron et al., 2007). While an increasing amount of cognitive offloading (e.g. in conditions with low temporal costs relative to conditions with high temporal costs) accelerates task processing (Morgan et al., 2009; Waldron et al., 2007), it subsequently diminishes recall performance for visuo-spatial information (Morgan et al., 2009; 2013; Waldron et al., 2007). Further, an increased amount of offloading was harmful for resumptions (i.e. continuing to rebuild the color pattern from one's memory) after task interruptions (Morgan et al., 2009; 2013). However, the reported studies tested the memory for the offloaded information immediately after offloading, thus not exceeding the duration of working memory maintenance (Morgan et al., 2009; 2013; Waldron et al., 2007). It still remains unclear whether the detrimental effects of offloading also persist at longer time intervals, thus affecting long-term memory. This is especially important, as in real-life situations we often offload information in order to access this information at a later stage (i.e. writing a shopping list or using a calendar). The question thereby arises whether offloading information into a technical tool would also be harmful for long-term memory acquisition.

With regard to the question of long-term memory acquisition, the awareness of the relevance of the offloaded information for subsequent testing might alter offloading behavior itself as well as potential consequences. This is because being aware of a subsequent test should induce the goal to foster learning in order to be prepared for later testing. On the one hand, cognitive offloading might not generally have detrimental effects on memory for the offloaded information but might even have beneficial long-term consequences when participants are explicitly instructed to memorize the studied material. For instance, it is commonly argued that cognitive offloading releases internal cognitive resources (Kirsh, 2010). In return, these released cognitive resources might serve to gain a deeper processing of the remaining task-relevant information and, therefore, improve memory (Craik & Lockhart, 1972) as well as learning (Salomon, 1990; Sweller et al., 1998). Consequently, someone who aims at acquiring long-term memory might strategically use cognitive offloading to form stronger memory representations.

On the other hand, however, if the released cognitive resources (due to offloading) cannot be directed to the remaining task-relevant information even with the explicit instruction to memorize the stimuli, the availability of technical tools might provide a risk for subsequent memory performance, as offloading decreases the overall amount of internal information processing and elaboration. In this case, strategic considerations should minimize cognitive offloading in order to create desirable difficulties (i.e. conditions of learning that make it more difficult but increase learning; Bjork & Bjork, 2011). Introducing desirable difficulties by using more memory-intense strategies and less offloading might be more demanding but might also enhance learning and memory (Bjork & Bjork, 2011). Therefore, in our research we also directly tested whether the awareness of a follow-up memory test alters offloading behavior as well as its consequences.

Present research

In the present research, we systematically investigated how cognitive offloading affects subsequent memory for the offloaded information. In particular, we focused on the question how being aware of the relevance of the offloaded information for a subsequent task alters offloading and its potentially detrimental consequences. In Experiment 1, we started with a demonstration of the proposed trade-off between immediate beneficial effects of offloading on task processing and subsequent detrimental effects of cognitive offloading on memory. This experiment is similar to the experiments reported by Morgan et al. (2009; see also Morgan, et al., 2013; Waldron, et al., 2007) with the difference that our memory test was delayed substantially following the completion of the Pattern Copy Task, whereas Morgan et al. (2009) presented the memory test in between the trials of the Pattern Copy Task. Further, our memorized information consisted of more naturalistic stimuli (i.e. images of real-world objects) rather than colored squares. Nevertheless, due to the high similarity across the studies, our first experiment could be considered to be a conceptual replication of the findings of Morgan et al. (2009).

In Experiments 2 and 3, we studied how awareness of the upcoming memory test, and thus the goal to foster learning, influences offloading behavior as well as its consequences for memory. Because the Pattern Copy task is so complex that it cannot be solved without any offloading, it allowed us to test whether the detrimental effects of offloading also arise under conditions in which participants know that they will have to recall the offloaded information at a later point in time. With regard to cognitive offloading, we tested two competitive hypotheses. On the one hand, released cognitive resources due to offloading might be used to build long-term memory representations. If this is the case, offloading behavior would not be detrimental to long-term memory acquisition. On the other hand, if devoting released resources to the formation of long-term memory is not possible, offloading behavior would be detrimental for long-term memory acquisition. In this case, offloading behavior should be minimized in order to create desirable difficulties that improve learning. In order to distinguish between these hypotheses, we manipulated the awareness of a follow-up memory test and investigated whether test awareness alters the use and the effects of cognitive offloading. In Experiment 2, the participants performed the Pattern Copy Task under free choice conditions (i.e. the participants could freely choose whether to offload or not). In the final Experiment 3, we compared this free choice conditions with a condition in which we enforce offloading to the maximum extent.

Experiment 1

This experiment focused on demonstrating the proposed trade-off between immediate task performance and the formation of memory representations. Our participants completed a version of the Pattern Copy Task which clearly exceeds working memory capacity. Therefore, all participants had to rely on offloading behavior although the amount of offloading might have varied between them. In this task, increasing offloading behavior reduced the amount of information that needed to be handled simultaneously within working memory. Importantly, however, each participant had to process every unit of information to solve the task. Beyond measuring individual offloading behavior, we manipulated the temporal costs of offloading in order to alter the amount of cognitive offloading (i.e. higher costs of externalization induce a stronger reliance on internal resources). Following a retention interval at the end of the experiment, the participants completed an unexpected memory test. We predicted that more offloading increases immediate task performance with regard to efficiency (speed and accuracy) but impairs the formation of memory representations.

Except for the retention interval exceeding the duration of working memory as well as the more naturalistic objects to memorize, our task and procedure is similar to the experiments reported in Morgan et al. (2009). Due to these similarities, our first experiment could be considered to reflect a conceptual replication of the previously established result pattern. Nevertheless, we consider it important to replicate previous findings with novel variants of tasks to prove the generalizability of the concepts under study as well as the suitability of the present materials and procedure.

Method

This experiment was preregistered at the Open Science Framework (OSF; https://osf.io/n64cd). Additionally, all materials, data, and analysis scripts are available at https://osf.io/vmgd4/.

Participants

Our final sample consisted of 172 students (131 females; 18 - 47 years) recruited at the University of Tübingen. The participants received course credit or a financial compensation of 8€ for one hour of their time. The study was approved by the ethical board of the Leibniz-Institut für Wissensmedien, Tübingen, Germany, and all participants provided informed consent prior to testing. The sample size was preregistered and intended to achieve a statistical power of $(1 - \beta) = .90$ at medium effect sizes of $d = 0.50$. The participants were randomly assigned to one of the two conditions ($n = 86$ per condition). According to the preregistered exclusion criteria, data from participants with missing data (16), failures in complying with the instructions (5), a priori awareness of the surprise memory test (14)[6], too many errors in the working memory tests to compute capacity (1), or too large deviations (+/- 3 *SD*) in any dependent variable of the Pattern Copy Task or the memory test (15) were replaced. Each participant performed the experiment individually in a testing room.

[6] Exploratory analyses showed that all reported results and conclusions remained equivalent when participants who reported a priori test awareness were included in the analyses ($N = 186$).

Apparatus

All tasks were controlled by PsychoPy scripts (Peirce, 2007) running on 12.3'' Microsoft Surface Pro tablets (2736 x 1824 pixels; touch served as input device) lying flat on the table at a viewing distance of approximately 36 cm.

Tasks and Stimuli

Pattern Copy Task. This task was designed to measure cognitive offloading behavior (Ballard et al., 1995). The participants dragged-and-dropped 12 images of distinct objects (each 3.5 x 3.5 deg; selected from the *Bank of standardized stimuli;* Brodeur, Dionne-Dostie, Montreuil, & Lepage, 2010; Brodeur, Guérard, & Bouras, 2014) from a resource window in the lower right screen to a workspace window in the upper right screen. The aim was to replicate a layout of the same objects from an identically shaped model window in the upper left area of the screen (see Figure 8A). At any time, either the model or the workspace window was visible while the other window was covered. The participants were able to open the model window by using a slider on the right side of that window and the workspace window by touching a bar left to it. For one half of the participants, opening the model window resulted in a delay of two seconds (for which the slider turned red). Therefore, these participants had to wait in order to open the model window (lockout condition), whereas the remaining half of the participants could open the model window immediately (no lockout condition; see e.g. Gray et al., 2006; Grinschgl et al., 2020; for a similar manipulation). The participants were allowed to switch between the two windows as often as they wanted. At the beginning of each trial, gray masks covered all windows, and the participants could decide which window to open first. After rebuilding the 12 images, they pressed a button in the lower left area of the screen to continue. There were 20 trials with distinct spatial arrangements of the patterns to be copied, preceded by one practice trial. The images showed (colored) common objects from everyday life such as kitchenware, clothing, or food products (for a further description see Brodeur et al., 2010; 2014; all images we used are available on https://osf.io/vmgd4/). A new set of images was selected randomly without replacement from a collection of 480 objects (240 for the Pattern Copy Task; 240 additional distractors for the memory test) for each trial. The sets of images were counterbalanced across conditions (i.e. one participant from each condition saw the same sets of objects in the same order).

As proxies for cognitive offloading, we analyzed the number of openings of the model window (i.e. openings of the model window), the duration of the very first opening (i.e. initial encoding duration), and the number of correctly copied items following the first opening of the model window (i.e. initially correctly copied items; only the first opening within a trial is independent of preceding openings). More pronounced offloading behavior is indicated by opening the window more often as well as shorter initial encoding durations and fewer initially correctly copied objects. Furthermore, as immediate task performance, we measured the trial duration (corrected for the two second lockout-times) as well as the number of errors. The number of errors refers to the number of incorrectly rebuild images at the end of a trial. Higher trial duration and more errors indicate lower immediate task performance.

Memory Test. This task was designed to assess memory performance for the objects handled in the Pattern Copy Task. The participants' task was to restore each of the 20 unique spatial arrangements of objects from the Pattern Copy Task from their memory (see Figure 8B). In each trial, one of the grids was presented in the center of the screen. Next to the grid, the original 12 images of this particular grid were presented intermixed with 12 new distractor images from the same database that had not been presented before (each 3.5 x 3.5 deg). The participants were instructed to rebuild the original arrangement by drag-and-dropping the correct images to the correct locations within the arrangement. As proxies for memory performance, we calculated the proportion of correctly restored identity-location bindings (i.e. correct image at the correct location). We calculated this proportion relative to both the reproduced pattern in the Pattern Copy Task (i.e. identity-location bindings corrected) as well as the original pattern within the Pattern Copy Task (i.e. identity-location bindings). We conducted this two-fold analysis to exclude the possibility of our results emerging from carry-over effects of initial copy errors. Furthermore, we calculated the proportion of correctly restored identities (i.e. correct image in any location; identity).

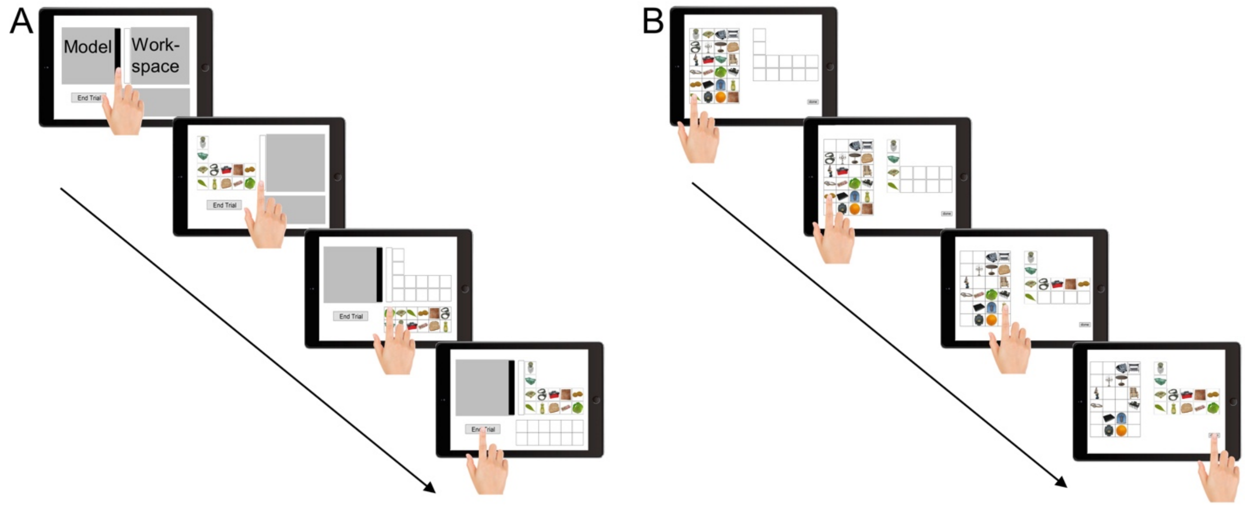

Figure 8. Illustration of the Pattern Copy Task and Memory Test. (A) Pattern Copy Task. Participants copied the layout of images from the model window (left) to a workspace window (right). Importantly, only one of the windows was visible at a time. This task measures offloading behavior (i.e. the amount of simultaneously copied images) as well as the immediate task performance (i.e. speed and accuracy). On a group level, we induced offloading behavior by manipulating the temporal costs of accessing the model window. (B) Memory Test. The participants restored the configurations of the Pattern Copy Task from memory. (Tablet frame designed by Freepik; Index finger designed by Jannoon028 / Freepik.)

Additional Tests. Between the Pattern Copy Task and the memory test, our participants completed two additional working memory tests as a proxy for their working memory capacity without offloading. In the first test, the participants had to reconstruct visual patterns of colored squares (*Visual Patterns Test*; adapted from Della Sala et al., 1999). In the second task, the participants had to reconstruct a temporal sequence of spatial locations (*Corsi Blocks Task*; adapted from Milner, 1971). Both tests followed an adaptive staircase of difficulty (starting with

2 objects, +1 object if correct, -1 object if false, minimum of 2 objects), and we analyzed the set size of the last 10 correctly solved trials (out of a total of 30 trials).

Results

In line with our preregistered hypothesis, the participants in the no lockout condition performed more cognitive offloading and had a higher efficiency in immediate task performance, but subsequently showed less accurate memory performance. Further, individual differences in offloading behavior revealed the same pattern of results.

Cognitive Offloading

For all three proxies of cognitive offloading, *t*-tests for independent samples indicated more offloading in the no lockout than in the lockout condition (see Table 8). The participants in the no lockout condition opened the model window more frequently, $t(170) = 7.55$, $p < .001$, $\eta_p^2 = .25$, 95% CI [.15; .35], showed a shorter initial encoding of the model window, $t(170) = -3.87$, $p < .001$, $\eta_p^2 = .08$, 95% CI [.02; .17], and copied fewer items correctly within the first copy cycle, $t(170) = -4.13$, $p < .001$, $\eta_p^2 = .09$, 95% CI [.03; .18], in comparison to those participants in the lockout condition.

Table 8. *Means and Standard Errors of Dependent Variables in Experiment 1*

	No Lockout		Lockout		Test Statistics		
	M	*SE*	*M*	*SE*	$t(170)$	p	η_p^2
Cognitive Offloading:							
Openings of the Model Window	3.61	0.15	2.31	0.09	7.55	<.001	.25
Initial Encoding Duration (sec)	13.99	0.89	20.14	1.31	-3.87	<.001	.08
Initially Correctly Copied Items	5.45	0.28	7.22	0.32	-4.13	<.001	.09
Immediate Task Performance:							
Trial Duration (sec)	49.33	1.19	55.06	1.25	-3.31	.001	.06
Errors	0.19	0.04	0.21	0.03	-0.37	.709	<.01
Memory Performance:							
Identity	10.55	0.11	10.93	0.09	-2.76	.006	.04
Identity-Location Bindings	5.91	0.30	7.07	0.33	-2.59	.010	.04
Identity-Location Bindings (corrected)	5.91	0.30	7.08	0.33	-2.63	.009	.04
Working Memory Capacity:							
Visual Patterns Test	3.84	0.05	3.89	0.05	-0.56	.576	<.01
Corsi Blocks Task	4.76	0.07	4.73	0.08	0.23	.820	<.01

Note: Cognitive offloading (openings of the model window and initial encoding duration), immediate task performance, and working memory capacity refer to open-ended count or time data. Initially correctly copied items and memory performance refer to count data with a maximum of 12.

Immediate Task Performance

Two *t*-tests for independent samples showed that participants in the no lockout condition solved the Pattern Copy Task more efficiently than participants in the lockout condition (see Table 8; values are corrected for lockout times). In other words, they solved the task in less time, $t(170) = -3.31$, $p = .001$, $\eta_p^2 = .06$, 95% CI [.01; .14], without decrements in accuracy, $t(170) = -0.37$, $p = .709$, $\eta_p^2 < .01$, 95% CI [.00; .03]. With on average below one error per trial in both groups, performance in terms of accuracy was at ceiling.

Memory Performance

While being more efficient in immediate task performance, the participants in the no lockout condition performed less accurately in the unexpected memory test (see Table 8). A series of t-tests for independent samples confirmed that the participants in the no lockout condition remembered the identity of the involved images, $t(170) = -2.76$, $p = .006$, $\eta_p^2 = .04$, 95% CI [.003; .12], as well as uncorrected, $t(170) = -2.59$, $p = .010$, $\eta_p^2 = .04$, 95% CI [.002; .11], and corrected (i.e. for errors in the Pattern Copy Task) identity-location bindings, $t(170) = -2.63$, $p = .009$, $\eta_p^2 = .04$, 95% CI [.002; .11], worse than the participants in the lockout condition. In other words, a high degree of cognitive offloading in the no lockout condition negatively affected subsequent memory accuracy. This finding was further emphasized by an exploratory analysis of individual differences, which showed strong correlations between offloading behavior and memory accuracy (see Table 9 and Figures S1.1, S1.2 and S1.3 in the electronic supplementary material (ESM) for the corresponding scatter plots). In both experimental conditions, Pearson-correlations showed that increasing offloading behavior was clearly associated with decreasing memory accuracy across all proxies for offloading and memory, all $|r|s(84) >= .51$, all $ps < .001$.

Table 9. *Pearson-Correlations Between Cognitive Offloading and Memory Performance in Experiment 1*

	Identity	
	No Lockout	Lockout
Openings of the Model Window	-.54***	-.61***
Initial Encoding Duration (sec)	.51***	.63***
Initially Correctly Copied Items	.68***	.70***
	Identity-Location Bindings	
	No Lockout	Lockout
Openings of the Model Window	-.58***	-.69***
Initial Encoding Duration (sec)	.65***	.67***
Initially Correctly Copied Items	.85***	.79***
	Identity-Location Bindings (corrected)	
	No Lockout	Lockout
Openings of the Model Window	-.58***	-.69***
Initial Encoding Duration (sec)	.65***	.67***
Initially Correctly Copied Items	.85***	.79***

Note: * $p < .05$, ** $p < .01$, *** $p < .001$

Mediation Analyses

An alternative explanation for improved memory performance in the lockout condition is that this benefit does not stem from the reduction in offloading behavior but that participants take advantage of the two seconds lockout for additional rehearsal in this condition. In order to provide evidence that reduced offloading behavior indeed increased memory performance, we conducted a set of exploratory mediation analyses. Within these analyses, we probed whether our independent variable, temporal lockout, directly affected subsequent memory performance or whether this relationship was mediated by cognitive offloading (see Table 10). We observed a mediated effect of the predictor lockout (no lockout/lockout) via cognitive offloading (mediator) on all three memory variables (identity, identity-location bindings, identity-location bindings corrected), all mediated effects >= 0.58, all ps < .001. In fact, the mediations substantially reduced all direct effects of the predictor on the memory performance measures, all

|direct effects| <= 0.86, all *p*s > .040. Only in two cases (out of nine), did the direct effect remain significant. This indicates that the reduction in offloading behavior accompanying temporal lockouts rather than the lockout manipulation itself enhanced memory performance.

Table 10. *Mediation Analyses With the Predictor Lockout (No Lockout/Lockout), Mediator Cognitive Offloading and Outcome Memory Performance in Experiment 1*

	Identity			
	Mediated Effect	95% CI	Direct Effect	95% CI
Openings of the Model Window	0.58***	[0.41; 0.83]	-0.20	[-0.43; 0.06]
Initial Encoding Duration (sec)	0.29***	[0.16; 0.47]	0.09	[-0.17; 0.29]
Initially Correctly Copied Items	0.39***	[0.20; 0.58]	-0.01	[-0.23; 0.19]
	Identity-Location Bindings			
Openings of the Model Window	2.01***	[1.48; 2.55]	-0.86*	[-1.65; -0.05]
Initial Encoding Duration (sec)	1.13***	[0.63; 1.70]	0.02	[-0.73; 0.62]
Initially Correctly Copied Items	1.50***	[0.74; 2.29]	-0.34	[-0.92; 0.17]
	Identity-Location Bindings (corrected)			
Openings of the Model Window	2.01***	[1.54; 2.63]	-0.84*	[-1.59; -0.05]
Initial Encoding Duration (sec)	1.13***	[0.58; 1.72]	0.04	[-0.65; 0.73]
Initially Correctly Copied Items	1.50***	[0.81; 2.23]	-0.33	[-0.78; 0.21]

Note: * $p < .05$, ** $p < .01$, *** $p < .001$; all mediation analyses were conducted with a bootstrapping procedure (1000 simulations) using the package “mediation” in R (Tingley, Yamamoto, Hirose, Keele, & Imai, 2014).

Working Memory Capacity

Two *t*-tests for independent samples confirmed that there were no group differences between participants in the lockout and the no lockout condition with regard to memory capacity as measured by the Visual Patterns Test, $t(170) = -0.56$, $p = .576$, $\eta_p^2 < .01$, 95% CI [.00; .03], $BF_{10} = 0.19$ and the Corsi Blocks Task, $t(170) = 0.23$, $p = .820$, $\eta_p^2 < .01$, 95% CI [.00; .02], $BF_{10} = 0.17$ (see Table 8). Exploratory correlational analysis of working memory capacity, cognitive offloading, and subsequent memory performance are available in Table S1 of the ESM.

Experiment 2

The observation that more cognitive offloading impairs the formation of memory representation in Experiment 1 arises from an incidental experimental setup (i.e. participants were not aware of the memory test while performing the Pattern Copy Task). Whereas this finding shows impaired memory for situations with implicit formation of new memory representations, it does not necessarily transfer to scenarios in which participants explicitly aim at forming memory representations for subsequent testing. In the second experiment, we therefore investigated how awareness of the subsequent memory test alters offloading behavior as well as the formation of memory representations. To study this, we added a new factor to the design of Experiment 1. Whereas one half of the participants remained uninformed with regard to the subsequent memory test, we explicitly informed the other half of the participants that they would have to complete a memory test after the Pattern Copy Task. With this setup, we tested two competing hypotheses. The first hypothesis is that cognitive offloading releases internal cognitive resources and that test awareness is necessary in order to devote these released resources to the formation of memory representations. The second hypothesis is that released resources do not contribute to the formation of memory representations. In this case, the participants might rely more on their own internal encoding strategies and thus avoid cognitive offloading in order to foster long-term learning (i.e. a desirable difficulty).

Method

This experiment was preregistered at the OSF (https://osf.io/pb89m). All materials, data and analysis scripts are available at https://osf.io/ke9dj/.

Participants

The final sample size consisted of 172 students (137 females; 18-35 years), who were randomly assigned to the four conditions (*n* = 43 per condition) and tested individually in a testing room. According to the preregistered exclusion criteria, we replaced data from participants with missing data (1), a priori awareness of the surprise memory test (19)[7], or too large deviations (+/- 3 *SD*) in any dependent variable of the Pattern Copy Task or the memory test (4). These exclusion criteria were identical to those of Experiments 1 and 3.

Tasks and Stimuli

All tasks and stimuli were identical to Experiment 1 with the exceptions described in this section.

Pattern Copy Task. For one half of the participants, the instructions included information announcing the upcoming memory test at the end of the experiment (translated from German: "Please note: Following the task, you will have to take a memory test which will test your memory of the presented patterns of images."). Additionally, before the first trial of the Pattern Copy Task, the participants were reminded about the memory test (translated from German: "Please try to remember the pictures and patterns as well as possible, as a recognition test will be carried out after this test."). For the other half of the participants, none of this information about the upcoming memory test was included in the instructions. The original instructions for each condition as well as the tests themselves are available at https://osf.io/ke9dj/.

[7] When exploratorily including participants that were excluded due to false memory test awareness in the analysis (*N* = 191), the results remain essentially the same.

As the focus of this experiment was on the effect of offloading on subsequent memory rather than immediate task performance, we aimed to ensure that all participants had the same chance to remember the initial pattern of objects. Therefore, the participants had to solve the Pattern Copy Task correctly in this experiment. Consequently, the participants could not proceed to the next trial without correctly replicating the layout from the model window. Nevertheless, we will still report trial duration as an index of immediate task performance. The patterns of this experiment consisted of eight images only (these images are a subset of the images used in Experiment 1; see https://osf.io/ke9dj/).[8]

Memory Test. The layout within the memory test was slightly different. The eight original and eight distractor images were presented below instead of next to the corresponding grid. As we used fewer images (compared to the other experiments), this adapted layout was more user-friendly.

Results

Matching the results of Experiment 1, more offloading resulted in faster task processing but less accurate memory performance. Interestingly, participants who knew about the subsequent memory test reduced offloading behavior and subsequently showed an improved memory performance.

[8] Full disclosure: We conducted Experiment 2 before Experiments 1 and 3. As participants performed rather well on the memory test in this experiment, we increased the number of images for Experiment 1 and 3.

Cognitive Offloading

We analyzed all three proxies for cognitive offloading using 2 x 2 between-subjects ANOVAs with lockout and announcement of the memory test as the independent variables. Each proxy of cognitive offloading indicated more offloading in the no lockout than in the lockout condition (see Table 11). The participants in the no lockout condition opened the model window more frequently, $F(1, 168) = 37.25$, $p < .001$, $\eta_p^2 = .18$, 95% CI [.09; .28], showed a shorter initial encoding of the model window, $F(1, 168) = 15.58$, $p < .001$, $\eta_p^2 = .09$, 95% CI [.02; .17], and copied fewer items correctly within the first copy cycle, $F(1, 168) = 24.50$, $p < .001$, $\eta_p^2 = .13$, 95% CI [.05; .22], than the participants in the lockout condition. Further, across all variables, the participants in the uninformed condition offloaded more than the participants in the informed condition. Thus, the participants in the uninformed condition opened the model window more frequently, $F(1, 168) = 10.31$, $p = .002$, $\eta_p^2 = .06$, 95% CI [.009; .14], showed a shorter initial encoding of the model window, $F(1, 168) = 19.29$, $p < .001$, $\eta_p^2 = .10$, 95% CI [.03; .19], and copied fewer items correctly within the first copy cycle, $F(1, 168) = 12.21$, $p < .001$, $\eta_p^2 = .07$, 95% CI [.01; .15], than the participants in the informed condition. No interactions between the conditions were found, all $Fs(1, 168) <= 1.83$, all $ps >= .178$.

Table 11. *Means and Standard Errors of Dependent Variables in Experiment 2*

	No Lockout				**Lockout**			
	Uninformed		**Informed**		**Uninformed**		**Informed**	
	M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Cognitive Offloading:								
Openings of the Model Window	2.49	0.15	1.98	0.13	1.65	0.09	1.45	0.07
Initial Encoding Duration (sec)	9.52	0.80	14.08	1.18	13.63	1.01	17.83	0.95
Initially Correctly Copied Items	4.73	0.27	5.72	0.28	6.09	0.25	6.87	0.19
Immediate Task Performance:								
Trial Duration (sec)	28.85	0.99	32.73	1.05	33.76	1.24	36.79	1.15
Memory Performance:								
Identity	6.99	0.12	7.32	0.09	7.27	0.14	7.66	0.04
Identity-Location Bindings	4.20	0.29	5.17	0.29	5.24	0.31	6.28	0.19
Working Memory Capacity:								
Visual Patterns Test	3.88	0.08	3.95	0.07	3.76	0.09	3.95	0.09
Corsi Blocks Task	4.61	0.10	4.79	0.09	4.60	0.09	4.87	0.10

Note: Cognitive offloading (openings of the model window and initial encoding duration), immediate task performance, and working memory capacity refer to open-ended count or time data. Initially correctly copied items and memory performance refer to count data with a maximum of 8.

Immediate Task Performance

With regard to immediate task performance, more cognitive offloading came along with faster task processing (see Table 11). We confirmed this with an exploratory 2 x 2 between-subjects ANOVA with lockout and announcement of the memory test as the independent variables and trial duration as the dependent variable. This ANOVA revealed that the participants in the no lockout condition completed the trials faster than the participants in the lockout condition, $F(1, 168) = 16.24$, $p < .001$, $\eta_p^2 = .08$, 95% CI [.02; .18] (trial duration was corrected for lockout-times). Further, the participants in the uninformed condition completed the trials faster than the participants in the informed condition, $F(1, 168) = 9.62$, $p = .005$, $\eta_p^2 = .05$, 95% CI [.01; .13]. The interaction between both conditions was not significant, $F(1, 168) = 0.14$, $p = .706$.

Memory Performance

While offloading more within the Pattern Copy Task, the participants in the no lockout condition as well as the uninformed condition performed less accurately in the memory test (see Table 11). We analyzed both proxies for memory accuracy using 2 x 2 between-subjects ANOVAs with lockout and announcement of the memory as the independent variables. The participants in the no lockout condition performed less accurately in identifying the involved images, $F(1, 168) = 8.29$, $p = .004$, $\eta_p^2 = .05$, 95% CI [.005; .12]), as well as in retrieving identity-location bindings, $F(1, 168) = 15.09$, $p < .001$, $\eta_p^2 = .08$, 95% CI [.02; .17], in comparison to the participants in the lockout condition. Further, uninformed participants performed less accurately in identifying the involved images, $F(1, 168) = 11.58$, $p < .001$, $\eta_p^2 = .06$, 95% CI [.01; .14], and the identity-location bindings, $F(1, 168) = 13.20$, $p < .001$, $\eta_p^2 = .07$, 95% CI [.02; .16], than informed participants. There was no interaction between the investigated conditions, all $Fs(1, 168) <= 0.08$, all $ps >= .773$. These findings were further supported by the exploratory analyses of individual differences which showed correlations between offloading behavior and memory accuracy (see Table 12; scatter plots of all correlations are available in the ESM Figures S2.1 and S2.2). Increasing offloading behavior was associated with decreasing memory accuracy.

Table 12. *Pearson-Correlations Between Cognitive Offloading and Memory Performance in Experiment 2*

	Identity			
	No Lockout		Lockout	
	Uninformed	Informed	Uninformed	Informed
Openings of the Model Window	-.70***	-.47**	-.55***	-.37*
Initial Encoding Duration (sec)	.53***	.47**	.40**	.29
Initially Correctly Copied Items	.67***	.57***	.55***	.42**
	Identity-Location Bindings			
	No Lockout		Lockout	
	Uninformed	Informed	Uninformed	Informed
Openings of the Model Window	-.53***	-.58***	-.61***	-.64***
Initial Encoding Duration (sec)	.45**	.60***	.35*	.47**
Initially Correctly Copied Items	.53***	.69***	.65***	.68***

Note: * $p < .05$, ** $p < .01$, *** $p < .001$

Mediation Analyses

As in Experiment 1, we conducted a set of exploratory mediation analyses in order to provide evidence that the reduction of offloading behavior increased memory accuracy in the lockout conditions (see Table 13). We observed a mediated effect of the predictor lockout (no lockout/lockout) via cognitive offloading (mediator) on all memory variables (identity, identity-location bindings), all mediated effects >= 0.18, all *p*s <= .001, all |direct effects| <= 0.53, all *p*s >= .046. In only one case (out of 6), the direct effect remained significant while the mediating factor still appears to be the stronger predictor. Hence, the lockout manipulation influenced subsequent memory performance by affecting offloading behavior. Further, regarding the announcement of the upcoming memory test (informed/not informed), we also observed a mediation of the effect of announcement via cognitive offloading, all |mediated effects| >= 0.18, all *p*s <= .004, rather than a direct effect on subsequent memory performance, all

|direct effects| <= 0.50, all *p*s >= .026 (see Table 14). In two cases (out of 6), the direct effect remained significant; however, the mediated effect appears to be stronger overall.

Table 13. *Mediation Analyses With the Predictor Lockout (No Lockout/Lockout), Mediator Cognitive Offloading and Outcome Memory Performance in Experiment 2*

	Identity			
	Mediated Effect	95% CI	Direct Effect	95% CI
Openings of the Model Window	0.36***	[0.22; 0.56]	-0.06	[-0.29; 0.16]
Initial Encoding Duration (sec)	0.18***	[0.08; 0.32]	0.12	[-0.12; 0.30]
Initially Correctly Copied Items	0.30***	[0.18; 0.48]	-0.003	[-0.23; 0.17]
	Identity-Location Bindings			
Openings of the Model Window	0.99***	[0.68; 1.35]	0.09	[-0.42; 0.60]
Initial Encoding Duration (sec)	0.55***	[0.29; 0.89]	0.53*	[0.01; 1.06]
Initially Correctly Copied Items	0.90***	[0.52; 1.32]	0.17	[-0.33; 0.67]

Note: * *p* < .05, ** *p* < .01, *** *p* < .001; all mediation analyses were conducted with a bootstrapping procedure (1000 simulations) using the package “mediation” in R (Tingley et al., 2014).

Table 14. *Mediation Analyses With the Predictor Announcement of the Memory Test (Informed/Uninformed), Mediator Cognitive Offloading and Outcome Memory Performance in Experiment 2*

	Identity			
	Mediated Effect	95% CI	Direct Effect	95% CI
Openings of the Model Window	-0.18**	[-0.32; -0.06]	-0.18*	[-0.36; -0.03]
Initial Encoding Duration (sec)	-0.20***	[-0.31; -0.10]	-0.15	[-0.32; 0.02]
Initially Correctly Copied Items	-0.21***	[-0.37; -0.09]	-0.15	[-0.33; 0.00]
	Identity-Location Bindings			
Openings of the Model Window	-0.50**	[-0.83; -0.19]	-0.50*	[-0.99; -0.05]
Initial Encoding Duration (sec)	-0.62***	[-1.02; -0.32]	-0.39	[-0.88; 0.18]
Initially Correctly Copied Items	-0.63**	[-1.04; -0.26]	-0.38	[-0.82; 0.08]

Note: * *p* < .05, ** *p* < .01, *** *p* < .001; all mediation analyses were conducted with a bootstrapping method (1000 simulations) using the package “mediation” in R (Tingley et al., 2014).

Working Memory Capacity

We analyzed both proxies for working memory capacity using 2 x 2 between-subjects ANOVAs with lockout and announcement of the memory test as the independent variables. We did not find any main effects or interactions in working memory capacity for identity-location bindings as measured by the Visual Patterns Test, all *Fs*(1, 168) <= 2.38, all *ps* >= .13, all BF_{10}s <= 0.50 (see Table 11). In the Corsi Blocks Task, the participants in the uninformed condition showed a lower working memory capacity for temporal sequence of spatial locations, than the participants in the informed condition, $F(1, 168) = 4.85$, $p < .029$, $\eta_p^2 = .03$, 95% CI [.00; .09], $BF_{10} = 1.57$. However, performance in the Corsi Blocks Task was uncorrelated with cognitive offloading, all $|r|s(41) <= .21$, all *ps* > .173, as well as memory performance in the main task, all $|r|s(41) <= .21$, all *ps* > .166 (exploratory analyses; see Table S2 in the ESM). Therefore, we will not address this discrepancy any further. Nevertheless, please note, the Corsi Blocks Task was performed after the Pattern Copy Task in order to serve as a retention internal. Thus, it cannot be considered independent of our experimental design and differences in Corsi Blocks capacity might have been induced by our experimental manipulations. There were no other group differences or interactions in the Corsi Blocks Task, all *Fs*(1, 168) <= 0.12, all *ps* >= .66, all BF_{10}s <= 0.37 (see Table 11).

Experiment 3

Experiments 1 and 2 both showed that cognitive offloading was associated with reduced subsequent memory performance. When participants were aware of the upcoming memory test, however, they seem to reduce offloading behavior in order to foster long-term memory (Experiment 2). This finding suggests that cognitive resources which are released by offloading are rather "lost" than devoted to the acquisition of memory representations. In this third experiment, we further pursue on this finding by probing its' generality and/or boundaries. Therefore, we manipulated whether participants were allowed to freely choose their offloading behavior as in the previous experiments (choice condition) or whether they were forced to offload to a maximum extent (forced condition). Identically to Experiment 2, we further manipulated whether the participants were aware of the upcoming memory test (informed condition) or not (uninformed condition). If the cognitive resources that are released due to cognitive offloading cannot contribute to the formation of memory representations in general, being aware of the upcoming memory test should have no beneficial effect when the participants are forced to offload maximally. Furthermore, the condition with the free choice offloading also allows us to reinvestigate the interesting finding of Experiment 2, namely, that participants who were aware of the subsequent memory test rather avoided offloading in order to improve memory performance.

Method

We preregistered this experiment at OSF (https://osf.io/4ye2c). Further, all materials, data, and analysis scripts are available at (https://osf.io/k6t7q/). All methods of this experiment were identical to Experiment 1 and 2 with the exceptions described in this section.

Participants

Our final sample consisted of 172 new students (136 females; 18-66 years), randomly assigned to one of four experimental conditions (*n* = 43 per condition). Based on our preregistered exclusion criteria, we replaced data of participants with missing data (12), a priori awareness of the surprise memory test (27)[9], or too large deviations (+/- 3 SD) in any preregistered dependent variable of the Pattern Copy Task or the memory test (6). These exclusion criteria were identical to Experiments 1 and 2. This experiment was conducted in a group setting with a maximum of four participants at once. The testing room was divided into separate chambers by movable walls so that the participants could not see each other during the study.

Tasks and Stimuli

Pattern Copy Task. Identical to Experiment 2, the participants in the informed conditions were informed about the upcoming memory test before starting the Pattern Copy Task, whereas the participants in the uninformed conditions received no such instructions. Orthogonally to the memory test awareness, we manipulated whether participants could freely choose their offloading behavior (choice condition) or whether they were forced to offload to a maximum extent (forced condition). The choice condition was identical to the no lockout condition in Experiments 1 and 2. In the novel forced condition, the participants were only allowed to rebuild a single object in the workspace window within each copy cycle of the Pattern Copy Task. Therefore, the participants had to change between the model and the workspace window at least twelve times to rebuild the twelve images in this condition. In this experiment, the participants could open the model window by just clicking on the bar next to it (instead of using a slider as in Experiments 1

[9] Including these participants in the analysis (*N* = 199) turned the interactions between announcement of the memory test and offloading conditions from statistical significance into numerical trends (i.e., $.05 < p < .1$). However, as participants in the forced offloading condition still benefited from test awareness with regard to their memory performance, such a change would not have a major impact on the interpretation of the current study. Further, the group difference in the Corsi Blocks Task attenuates from statistical significance into a numerical trend when including participants with memory test awareness which deviated from their instructions. Please note, the Corsi Blocks Task was performed after the Pattern Copy Task in order to serve as a retention internal. It can thus not be considered independent of our experimental design, and differences in Corsi Blocks capacity might have been induced by our experimental manipulations.

and 2). For all conditions, the Pattern Copy Task had to be solved correctly (see also Experiment 2). As proxies of cognitive offloading, we preregistered the number of openings of the model window and the number of correctly copied items after the first opening[10]. Additionally, we also analyzed the trial duration as an index of immediate task performance.

Memory Test. The memory test was identical to Experiment 1.

Results

In line with our previous findings, we observed that cognitive offloading was detrimental to subsequent memory performance when participants were unaware of the upcoming memory test. Nonetheless, when participants were aware of the memory test, the detrimental effects of cognitive offloading on memory performance were less pronounced. In particular, the participants who were forced to offload to a maximum extent recovered remarkably from the lack of memory representations relative to their uninformed counterparts.

Cognitive Offloading

Because one half of our participants were forced to offload to a maximum extent, we analyzed offloading behavior only for the participants performing the task under the free choice conditions. First, we confirmed that the participants in the choice condition actually offloaded less extensively than maximum offloading. Therefore, we conducted one-sample *t*-tests for the informed and uninformed conditions. In both choice (sub-)conditions, the participants offloaded

[10] Due to the forced offloading condition in this experiment, the proxies for offloading were of minor relevance. Nevertheless, we analyzed the number of openings of the model window and the number of correctly copied items after the first opening to demonstrate that participants were offloading more when they were forced to do so than under free choice conditions.

less than they maximally could (see Table 15). We observed fewer openings of the model window in the choice/uninformed condition, $t(42) = -39.33$, $p < .001$, $d = 6.07$, 95% CI [4.75; 7.38], as well as the choice/informed condition, $t(42) = -43.18$, $p < .001$, $d = 6.66$, 95% CI [5.22; 8.10], compared to $\mu = 12$ (i.e. the minimum amount of opening the model window in the forced condition). Additionally, we also observed that the participants copied more items initially correctly in the choice/uninformed condition, $t(42) = 11.01$, $p < .001$, d = 1.69, 95% CI [1.23; 2.17], and the choice/informed condition, , $t(42) = 12.89$, $p < .001$, d = 1.98, 95% CI [1.47; 2.50], compared to $\mu = 1$ (i.e. the maximum amount of copied items in forced condition per opening). Therefore, consistent with the previous experiments, the participants in the choice condition relied on offloading, but they did not offload maximally.

Further, a two-sample *t*-test showed that offloading behavior in the choice sub-conditions did not differ between the conditions with and without announcement of the memory test. Hence, the participants in the choice/informed condition and the choice/uninformed condition did not differ in the openings of the model window, $t(84) = -0.39$, $p = .693$, $\eta_p^2 < .01$, 95% CI [.00; .03], as well as the initially correctly copied items, $t(84) = 0.78$, $p = .439$, $\eta_p^2 = .01$, 95% CI [.00; .04]. This finding contrasts with the observation of Experiment 2, in which memory test announcement under free choice conditions resulted in reduced offloading behavior. We will further elaborate on this in the General Discussion.

Table 15. *Means and Standard Errors of Dependent Variables in Experiment 3*

	Choice				**Forced**			
	Uninformed		**Informed**		**Uninformed**		**Informed**	
	M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Cognitive Offloading:								
Openings of the Model Window	3.68	0.21	3.79	0.19	12.36	0.04	12.29	0.03
Initially Correctly Copied Items	4.96	0.36	4.61	0.28	0.97	0.01	0.98	0.01
Immediate Task Performance:								
Trial Duration (sec)	42.56	1.48	45.38	2.98	35.35	1.59	45.36	2.37
Memory Performance:								
Identity	9.97	0.18	10.20	0.13	8.17	0.17	9.34	0.22
Identity-Location Bindings	4.69	0.41	5.18	0.43	1.84	0.18	4.18	0.45
Working Memory Capacity:								
Visual Patterns Test	3.87	0.06	3.97	0.07	3.81	0.08	3.87	0.08
Corsi Blocks Task	4.59	0.09	4.71	0.09	4.65	0.12	4.94	0.09

Note: Cognitive offloading (openings of the model window and initial encoding duration), immediate task performance, and working memory capacity refer to open-ended count or time data. Initially correctly copied items and memory performance refer to count data with a maximum of 12.

Immediate Task Performance

We analyzed trial duration (Each trial had to be solved correctly.) as a proxy for immediate task performance within the Pattern Copy Task. We observed a faster completion of the trials when participants were not aware of the upcoming memory test (uninformed condition) than when they expected the upcoming memory test (informed condition, see Table 15). A 2 x 2 exploratory between-subjects ANOVA with memory test announcement as well as offloading condition (forced vs. choice) confirmed that this difference was significant. The participants in the uninformed condition solved the task faster than the participants in the informed condition, $F(1, 168) = 8.54$, $p = .004$, $\eta_p^2 = .05$, 95% CI [.005; .12]. However, there was no main effect of the offloading condition, $F(1, 168) = 2.70$, $p = .102$, $\eta_p^2 = .01$, 95% CI [.00; .07], as well as no interaction between both variables, $F(1, 168) = 2.68$, $p = .103$, $\eta_p^2 = .01$, 95% CI [.00; .07].

Memory Performance

In the conditions forcing participants to offload maximally, awareness of the upcoming memory test increased memory performance almost to the level of the condition with free choice offloading behavior (see Figure 9). For both proxies of memory performance, we conducted a separate 2 x 2 between-subject ANOVA with announcement of the memory test and offloading condition as the independent variables as well as memory performance as the dependent variable. We observed interactions between the independent variables for both proxies of memory performance “identity”, $F(1, 168) = 6.89$, $p = .009$, $\eta_p^2 = .04$, 95% CI [.002; .11] , as well as “identity-location bindings”, $F(1, 168) = 5.99$, $p = .015$, $\eta_p^2 = .03$, 95% CI [.001; .10]. Additionally, all main effects in both analyses reached significance, all $F(1, 168)$s >= 13.92, all ps < .001, all η_p^2s >= .08.

To further investigate the interaction effects, we conducted two-sample t-tests. With regard to both memory variables (identity and identity-location bindings), we observed less accurate memory performance in the forced/uninformed condition than in all other groups, all $t(84)$s >= 4.17, all ps < .001, all η_p^2s >= .18. Further, we observed no difference in memory accuracy between the choice/informed and choice/uninformed conditions, all $t(84)$s <= 1.04, all ps >= .302, all η_p^2s <= .01. Whether or not the forced/informed condition reached the level of the free choice conditions differed between the two proxies of memory accuracy. When analyzing only the identity of the recalled objects, the participants in the forced/informed condition showed a lower recognition accuracy than the participants in the choice/informed condition as well as the choice/uninformed condition, all $t(84)$s >= 2.21, all ps <= .029, all η_p^2s >= .05. However, this difference was absent when analyzing identity-location bindings. Here, the participants in the forced/informed condition did not differ in their subsequent memory performance from the participants in the choice/informed condition as well as the participants in the choice/uninformed condition, all $t(84)$s <= 1.59, all ps >= .115, all η_p^2s <= .03.

In line with the previous two experiments, exploratory correlational analyses within the free choice conditions revealed that an increased amount of cognitive offloading was associated with a lower subsequent memory performance in the choice conditions (see Table 16; scatter plots of all correlations are available in Figure S3.1 and S3.2 of the ESM). Due to the study design, there was hardly any variance in offloading behavior in the forced condition. Therefore, we did not conduct correlational analyses for these groups. Further, we did not repeat the mediation analyses of Experiments 1 and 2 as we directly manipulated offloading behavior in this experiment.

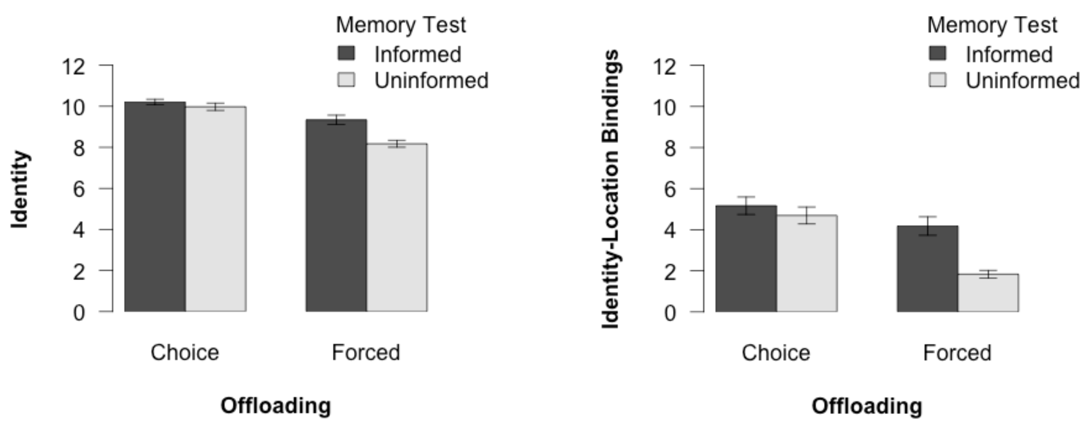

Figure 9. Interaction Effect of the Independent Variables Announcement of the Memory Test and the Offloading Condition on Memory Performance in Experiment 3. Error bars refer to the standard error of the mean.

Table 16. *Pearson-Correlations Between Cognitive Offloading and Memory Performance in Experiment 3*

	Identity	
	Choice	
	Uninformed	Informed
Openings of the Model Window	-.80***	-.55**
Initially Correctly Copied Items	.70***	.57***
	Identity-Location Bindings	
	Choice	
	Uninformed	Informed
Openings of the Model Window	-.69***	-.38*
Initially Correctly Copied Items	.78***	.60***

Note: * $p < .05$, ** $p < .01$, *** $p < .001$

Working Memory Capacity

With regard to the Visual Patterns Test, 2 x 2 between-subjects ANOVAs with announcement of the memory test and offloading condition as the independent variables revealed no group differences or interactions, all $Fs(1, 168) <= 1.25$, all $ps >= .265$, all η_p^2s < .01, all BF_{10}s <= 0.85 (see Table 15). With regard to the Corsi Blocks Task, the participants in the uninformed condition showed a lower working memory capacity for temporal sequences of spatial locations than the participants in the informed condition, $F(1, 168) = 4.43$, $p = .039$, $\eta_p^2 = .02$, 95% CI [.00; .09], $BF_{10} = 2.38$. This matches the results of the Corsi Blocks Task in Experiment 2. As the Visual Patterns Test and Corsi Blocks Task were conducted after the experimental manipulation in the offloading task (to delay the memory test), it therefore seems likely that the experimental manipulation induced the reduced Corsi Blocks capacity. Offloading behavior (in the free choice conditions), however, was uncorrelated with capacity in the Corsi Blocks Task, all $|r|s(41) <= .23$, all ps >= .138. Further, we observed no significant correlations between capacity in the Corsi Blocks Task and performance in the two memory measures all $|r|s(41) <= .28$, all ps >= .066 (exploratory analyses; see Table S3 in the ESM for all correlations). We observed no other group differences or interaction effects in the Corsi Blocks Task, all $Fs(1, 168) <= 1.96$, all $ps >= .163$, all η_p^2s $< .01$, all BF_{10}s $<= 0.69$. Given the absence of group differences in the Visual Patterns Test (which is conceptually closer to the Pattern Copy Task) as well as no correlations of the capacity in the Corsi Blocks Task, we will not address this issue any further.

Discussion

In the present research, we studied how offloading behavior affects memory performance for the offloaded information. In particular, we were interested in how the awareness of subsequent testing alters offloading behavior as well and its potentially detrimental consequences. Our first two experiments demonstrate that cognitive offloading induces a trade-off between immediate task performance in the Pattern Copy Task and the formation of memory representations for the information presented in this task (within the same experiments and participants). In other words, while cognitive offloading accelerated task processing, it interfered with the formation of memory for the processed information. This finding replicates and extends previous results reported by Morgan et al. (2009; see also Morgan, et al., 2013; Waldron, et al., 2007) on longer retention intervals exceeding working memory maintenance as well as on stimuli depicting naturalistic objects (rather than colored squares). This pattern of results appears to be genuine for an implicit formation of memory representations (i.e. Experiment 1 and the uninformed conditions of Experiment 2). Most importantly, the effect also arose when we directly manipulated offloading behavior in Experiment 3. When participants were unaware of the memory test, their memory performance was more accurate when they were offloading less under free choice conditions than when they were forced to offload to a maximum extent.

With regard to explicit formations of memory representations, the results were a bit more mixed. In Experiment 2, the participants who were aware of the upcoming memory test reduced their amount of cognitive offloading and subsequently revealed more accurate long-term memory performance. In the conditions with free choice in Experiment 3, however, we did not observe such a reduction of offloading behavior induced by the awareness of the upcoming memory test relative to the condition without such awareness. The lack of an equivalent effect with regard to reduced offloading behavior in order to foster learning raises questions regarding the generality, reliability, or magnitude of this effect. As the origin of this difference in the results pattern cannot be fully explained within this manuscript, we will only briefly discuss this finding below without drawing strong conclusions from it. A potential source for the diverging patterns might be that only one half of the participants performed the Pattern Copy Task under free choice conditions in Experiment 3 (the remaining participants were forced to offload and therefore could not adapt their offloading behavior). This reduction of statistical power or unexplained variance in the two samples seem to be plausible candidates as most other methods were virtually identical (despite the number of images). Nevertheless, what remained consistent in Experiments 2 and 3 is that the amount of offloading inversely matched the subsequent memory performance under free choice and informed conditions. Whereas the reduction of offloading in the informed conditions in Experiment 2 came along with more accurate subsequent memory, the absence of such a reduction in Experiment 3 was accompanied by the absence of differences in the subsequent memory tests. This consistency seems to suggest that there is a link between offloading and memory performance. Such a link would suggest that cognitive resources which remain "free" due to offloading are "lost" and do not contribute to the formation of memory. However, the forced offloading conditions in Experiment 3 prove the strong version of this argument to be wrong.

The results of Experiment 3 demonstrate that the amount of offloading does not necessarily determine memory accuracy. On the contrary, despite being forced to offload maximally, the participants in the forced/informed condition of this experiment showed almost the same memory accuracy as those participants in the choice/informed and choice/uninformed condition. Therefore, these conditions demonstrate that offloading does not necessarily have a detrimental impact on memory performance. Instead, at least under the extreme conditions of enforced maximum offloading, it seems to be possible to counteract the negative impact of offloading on the formation of memory (i.e. the released resources were not lost). This finding suggests that the announcement of the memory test and the corresponding induction of the specific goal to enhance memory accuracy contributes to the formation of long-term memory representations. What remains an open question for future research is why such beneficial effects of released resources do not arise with free choice offloading behavior. There are at least two speculative explanations for this pattern. First, it is possible that it is costly in terms of mental resources to coordinate a task solution at a medium memory load with a simultaneous medium use of released resources. Second, it could be that a minimum amount of released resources is necessary to reveal their positive effects. In the case of forced offloading, there are probably more "free" than "used" resources which might have enabled their impact on the general pattern of results.

A remarkable finding across all experiments are the high correlations between offloading behavior and memory performance on an individual level. These correlations were present within implicit (i.e. uninformed) as well as explicit (i.e. informed) setups of the experiments and support our findings on the group level in Experiments 1 and 2. More pronounced offloading behavior diminishes subsequent memory performance for the offloaded information. It seems important to note, however, that this correlational relationship is not deterministic. In this third experiment, we forced participants to offload to a maximum extent and observed differences on the group level in the memory performance despite constant offloading behavior on the individual level. An alternative explanation for our correlational results could be that individual differences in memory abilities induce both more offloading behavior as well as lower memory performance. In this case, participants who generally memorize information more accurately do not need to rely on offloading strategies as extensively as participants with lower memory abilities. However, our study was not designed to trace back individual differences. Both working memory tests were administered only after the experimental manipulation in order to prolong the retention interval. Thus, explaining the individual differences which we consistently observed across all experiments urges for further research exploring their causal relationship.

A central question for the interpretation of our results is whether offloading behavior itself impacts memory performance. Alternatively, the participants in the lockout conditions could have used the 2-second lockout-times to rehearse the visual information and thus showed an improved subsequent memory performance relative to participants in the no lockout conditions. In this case, the additional rehearsal time in the lockout condition rather than less cognitive offloading would have determined subsequent memory performance. Contrary to this view, however, our mediation analyses highlight the detrimental effects of offloading for the formation of memory representations. The impact of our manipulations (lockout/no lockout and informed/uninformed memory test) on subsequent memory performance was mediated by offloading behavior. This suggests that offloading behavior itself is associated with memory accuracy.

The Trade-Off of Cognitive Offloading

Beyond the conceptual replication of previous reports of a trade-off between immediate positive and subsequent negative effects of offloading memory processes in the Pattern Copy

Task (Morgan et al., 2009; 2013; Waldron et al., 2007), our results are also in line with studies reporting detrimental effects of cognitive offloading in other paradigms (Eskritt & Ma, 2014; Kelly & Risko, 2019a; O'Hara & Payne, 1998; Pyke & LeFevre, 2011; Sparrow et al., 2011). For instance, Pyke and LeFevre (2011) observed that using a calculator in an alphanumerical test led to a higher response accuracy but in return to a worse subsequent recall of the solution. They therefore concluded that using a calculator results in less active learning than self-generating answers. Studies such as this one show that using technical tools to offload cognitive processes diminishes long-term learning across various paradigms and cognitive functions. With regard to our Pattern Copy Task, temporarily high loads of working memory (i.e. copying multiple objects simultaneously) rather than continuously low loads (i.e. copying the objects sequentially) enhanced subsequent memory accuracy under free choice conditions, although all participants had to handle the same overall amount of information.

Please note that these temporarily high loads of working memory enhanced memory for the identity of the objects as well as their locations relative to each other. The general pattern of our findings matches the notion of desirable difficulties. Conceptually, desirable difficulties are supposed to enforce a more effortful and therefore more elaborate processing of information in order to enhance long-term learning (Bjork & Bjork, 2011). Thus, saving a lot of information internally places a high effort on internal cognitive resources which in return might lead to a deep processing of the information at hand and therefore fosters learning. Within this account, avoiding offloading behavior (such as in Experiment 2) in order to foster long-term learning could be seen as self-generated desirable difficulty. Nevertheless, as observed in Experiment 3, the relationship between offloading and memory is not fully deterministic. As differences in memory could also arise with the same amount of offloading, it remains possible that participants could use released cognitive resources to acquire more accurate memory representations.

Whether these released resources are employed in a manner that would be consistent with a self-generated desirable difficulty is one of the open questions to pursue in future research.

Our findings are also compatible with the framework of Salomon (1990) who proposed effects *with* technology on task processing as well as effects *of* technology on the development of cognitive abilities in the field of learning sciences. Effects *with* technology are supposed to affect immediate task processing due to utilizing technical tools, whereas effects *of* technology are potential long-term consequences (e.g., development of cognitive abilities) caused by preceding interactions with technology. Hence, cognitive offloading with technical tools might enable performance beyond internal cognitive limitations and thus increase immediate performance (Kirsh & Maglio, 1994; Salomon & Perkins, 2005). However, what users learn in this context appears to be how to effectively utilize the offloading device rather than solving the problem at hand with one's own cognitive abilities (Moritz et al., 2020). In return, it might be the absence of practice and routine in using internal resources which causes the detrimental effects of cognitive offloading (Risko & Gilbert, 2016; Salomon, 1990).

Positive consequences of cognitive offloading

Although Experiments 1 and 2, as well as the uninformed conditions in Experiment 3, constantly suggest that cognitive offloading is generally harmful for the formation of memory, one condition in our third experiment demonstrates that participants could counteract these detrimental effects under certain circumstances. In this experiment, we observed that the participants who were forced to offload to a maximum extent but were aware of the long-term memory test hardly differed in their memory performance from those participants who offloaded less under free choice conditions. This finding indicates that if it is necessary to acquire memory representations and there is no possibility to regulate offloading behavior, individuals can use released internal resources to improve memory performance. Please note that this improvement is relative to a condition in which participants are not aware of the subsequent memory test and therefore have no incentive to memorize the information. Overall, this improvement brings these participants (almost) back to the level of the participants who were able to freely choose their offloading behavior. As there is no benefit above the level of freely chosen offloading behavior, this might also be a reason why the participants in our Experiment 2 solved that task with more internal memory rather than with more offloading when they were aware of the memory test.

Our observation that participants in principle can take advantage of released resources matches a common argument in favor of cognitive offloading. One might consider that such released resources which come along with externalizations (Kirsh, 2010) could serve a deeper elaboration of the processed information (Sweller et al., 1998). In return, such a deeper elaboration could cause stronger memory representations (Craik & Lockhart, 1972). From the results of our experiments, it appears that such an argument rests on two essential preconditions. First, participants need to have the goal to foster long-term learning, as detrimental consequences under implicit learning conditions are likely. Without such a goal, released cognitive resources seem to be “lost”. Second, the amount of released cognitive resources needs to be substantially large to contribute to learning. In our experiments, we only observed such a contribution of released resources when we forced participants to complete the task with a minimum of internal resources. It appears likely that the same pattern of results would have emerged if our participants had completed the task with minimal internal memory themselves. This leads to the interesting hypothesis that a substantial amount of released resources can contribute to learning, whereas a small amount cannot. Future research should therefore study the relationship between the amount of released resources and their beneficial effects on learning.

It seems noteworthy that the announcement of upcoming memory tests does not generally result in beneficial effects of cognitive offloading. In an experiment reported by Sparrow et al. (2011), the participants transferred trivia statements into a computer document. Whereas the participants remembered fewer of these statements when they believed their document was saved in the computer rather than when they believed their document was erased, announcing the memory test had no effect on performance. Given the substantial differences between both paradigms (task, materials, difficulty, etc.), it seems hardly helpful to speculate about the origin of the differences in the results. Nevertheless, this discrepancy again shows that the interactions between the released resources due cognitive offloading and the goal of acquiring new mental representations is understudied and not well understood yet. Given the widespread distribution of modern technical tools that allow for cognitive offloading, however, a deeper understanding of this interaction is highly relevant to enable an appropriate usage of such tools.

Our experiments as well as those of Sparrow et al. (2011) focused on the interplay of offloading and memory accuracy for the offloaded information itself. Beyond the offloaded information itself, however, cognitive offloading could also affect cognitive performance for unrelated materials or in unrelated tasks (Runge et al., 2019; Storm & Stone, 2015). For instance, Storm and Stone (2015) observed that saving information in a technical tool before studying further information improved the memory performance of the latter information (i.e. reduced interference from the first information on the second). Further, there appear to be carry-over effects in offloading behavior between successive tasks (i.e. participants relying more on offloading in one task also rely more on offloading in a subsequent task; Storm, Stone, & Benjamin, 2016).[11]

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[11] For the interested readers, we added plots displaying offloading behavior across all trials and for each group within the Pattern Copy Task in the ESM (Figure S4, Figure S5, Figure S6). These plots show that participants mostly maintained their level of offloading after the first few trials for the rest of the task.

Cognitive offloading as a strategy

Given the growing impact on people's everyday lives by technical tools including external memories (Finley et al., 2018), a careful consideration of the apparent benefits and the hidden risks of cognitive offloading seems needed in order to avoid unintended detrimental long-term effects. First, it appears necessary to evaluate the goal of the task at hand. If the goal focuses on immediate performance, our study suggests that the adequate strategy would be increasing externalizations. In contrast, if the task's goal involves components of memorization or learning, different strategies should be applied. On the one hand, offloading behavior could be avoided in order to create desirable difficulties and foster learning. On the other hand – if avoiding offloading is not possible – released resources due to offloading could be activated to foster learning.

In Experiment 2, we observed that participants who were aware of the upcoming memory test offloading less but had a better memory than participants who were not aware of the upcoming memory test. This finding suggests that the participants might have been aware of the negative consequences of cognitive offloading or at least did not believe that cognitive offloading could be used beneficially. Thus, it appears that the participants decided to rely more on their internal memory rather than on externalizations. Critically, we did not observe such a change in offloading behavior based on the announcement of the memory test in Experiment 3 (choice condition). Therefore, we cannot conclude from our experiments whether participants do or do not have metacognitive knowledge about the impact of cognitive offloading on memory. Nevertheless, our findings from Experiment 2 urge for further research directly investigating how metacognitions about the impact of offloading alter offloading behavior across tasks with varying goals focusing either on immediate performance or subsequent memory. A plausible venue for such research to explore this question would be to directly manipulate metacognitions.

Conclusion

Taken together, we can derive the following insights from our experiments: First, there is a trade-off between positive immediate and negative subsequent consequences of cognitive offloading. Second, under free choice offloading, more cognitive offloading was associated with a lower subsequent memory performance on the group level as well as on the level of individual differences. Third, announcing subsequent testing could compensate for at least some of the detrimental effects of cognitive offloading on memory acquisition. Fourth, reducing the amount of offloading as a self-generated desirable difficulty as well as a taking advantage of released cognitive resources might reflect competing strategies when counteracting the detrimental effects of cognitive offloading. Fifth and finally, resources released by cognitive offloading only contribute to the formation of memories in explicit learning contexts (i.e. when participants have the goal to learn) but are rather “lost” without such a learning context.

Declaration regarding collaborative publications/manuscripts

The following chapter (Chapter 5) consists of a study that was designed together with Frank Papenmeier, Stephan Schwan, and Hauke S. Meyerhoff. Data collection had to be paused due to the Coronavirus-pandemic but will be resumed as soon as possible. After completing data collection, a manuscript will be prepared for publication. Parts of this experiment were conducted as a “Projektarbeit” of Lisa Marie Widmayer and Pauline Klöden. I am thankful to Deniz Geleri, Henri Nebel, Lisa Marie Widmayer, Elisabeth Arndt, Pauline Klöden, and Rebekka Hemmrich for their assistance in data collection.

Title of paper: *The impact of cognitive offloading on secondary task performance*
Status in publication process: Not published. Data collection needs to be continued (paused due to Covid-19).

5. Study 4

- The impact of cognitive offloading on secondary task performance -

In humans' daily life, the use of technical tools such as smartphones or tablets is ubiquitous. Technical tools are often used to support individuals' cognitive processing by externalizing important information (e.g., appointments, a shopping list) in the technical tool at hand instead of memorizing this information. This externalization of cognitive processes into technical tools is described as *cognitive offloading* (Risko & Gilbert, 2016). A main advantage of cognitive offloading is the opportunity to store more information at once than it would be possible with one's internal cognitive resources. A central limitation in the human cognitive architecture arises from working memory (Baddeley, 2003; Luck & Vogel, 2013), but due to cognitive offloading capacity limitations of working memory can be overcome (Risko & Gilbert, 2016). Individuals can flexibly distribute the cognitive demands of a task on technical tools and one's working memory which serves to lower working memory demand and makes a cognitive task less effortful. When offloading working memory processes task performance can be enhanced compared to when solely relying on internal working memory (Kirsh & Maglio, 1994; Risko & Gilbert, 2016). Thus, technical tools extend individuals' skills (Osiurak, et al., 2018) and can be accounted as an extended mind (Clark & Chalmers, 1998). Importantly, cognitive offloading is also supposed to release internal cognitive resources (Kirsh, 2010). When individuals offload information into technical tools that would otherwise need to be stored in working memory, working memory resources are saved. In the present study, we investigated if released cognitive resources due to the offloading of working memory processes in one task can be redirected and used to successfully perform a simultaneous secondary task.

Especially individuals' use of external representations such as diagrams or illustrations to solve problems as a form of cognitive offloading was assumed to release internal cognitive resources (Kirsh, 2010). External representations store information which can be used to facilitate problem-solving and thus such information does not need to be stored in one's memory. In turn, internal memory resources are released. Onto this account, researchers in the area of cognitive offloading (including us) assume that cognitive offloading releases internal cognitive resources (Kirsh, 2010; Risko & Gilbert, 2016). However, there are only a few studies that provide first insights into this potential release of cognitive resources due to offloading (Runge et al., 2019; Storm & Stone, 2015). The initial studies showed that cognitive offloading has positive effects on the subsequent processing of new information (Storm & Stone, 2015) or unrelated tasks (Runge et al., 2019) – potentially due to the release of internal cognitive resources.

In a study of Storm and Stone (2015) the participants had to learn a word list A which they then could either save in a computer file (i.e. offload the word list) or were not allowed to save (i.e. no offloading). Subsequently, they studied a word list B and performed a recall test. Storm and Stone (2015) showed that the offloading of the first word list A facilitated the learning and subsequent recall of the second word list B. When the participants were allowed to save the world list A in a computer file before studying the second word list B, their recall performance for the word list B was better than when they were not allowed to save the word list A. Interestingly, this was only the case when the offloading process was deemed reliable (i.e. word list A was successfully saved in the computer file). When the computer file did not successfully save word list A (i.e. offloading was not reliable), there was no advantage for memory recall of word list B. Successfully offloading the first word list seems to release internal cognitive resources that might be devoted to studying the second word list more elaborately (see Runge et al., 2020 for a replication of these results). This *saving-enhanced memory effect* shows that the offloading of irrelevant information can be used to support the encoding of new, relevant information. Runge et al. (2019) extended this finding by showing that released cognitive resources can be applied to perform an unrelated task. In their study, the participants also either offloaded a word list into a computer file or had to memorize the word list. Afterwards the participants performed an unrelated arithmetic task. The participants performed better in this arithmetic task (i.e. solved more problems correctly) when they had offloaded the previously studied word list compared to when they were not allowed to offload it but had to memorize it. Therefore, cognitive offloading also induced a *saving-enhanced performance effect.* Runge et al. (2019) concluded that cognitive offloading actually releases internal cognitive resources and that these released resources can even be utilized for the performance of a later, unrelated task. However, what still remains unclear is if such released cognitive resources can also be used instantaneously to perform a simultaneous, secondary task.

In the present experiment the participants performed a Pattern Copy Task (see Fu & Gray, 2000; Gray et al., 2006) that allowed the offloading of working memory processes. In this task the participants had to copy a color pattern from a model window into a workspace window. The participants could rely more on cognitive offloading and memorize less information at once by looking up the relevant information in the model window over and over again. In this task, the participants either experienced high temporal costs or low temporal costs of cognitive offloading. Previous research showed that the amount of cognitive offloading depends on cost-benefit considerations (e.g., Fu & Gray, 2000; Gray et al., 2006). Therefore, when the opening of the model window to access the relevant information is associated with high temporal costs (e.g., a temporal delay) the participants usually offload less working memory processes than when the opening of the model window is associated with low temporal costs (e.g., no temporal delay). A manipulation of the temporal costs within the Pattern Copy Task thus serves to experimentally manipulate the participants' amount of cognitive offloading and the related released cognitive resources. In addition to the Pattern Copy Task the participants either performed a simultaneous secondary task (N-back Task) or they did not perform such a task. We investigated how the manipulated temporal costs within the Pattern Copy Task as well as the presence of a secondary task impacts offloading behavior. Most importantly, we also investigated the effects of released internal resources due to the offloading of working memory processes on the performance of the secondary task. We expected that participants that offload more working memory processes due to low temporal costs within the Pattern Copy Task have more released internal resources that they can devote to the simultaneous performance of the secondary task compared to participants that offload less due to high temporal costs within the Pattern Copy Task. In turn, more released internal cognitive resources should increase secondary task performance compared to less released internal cognitive resources.

Method

This experiment was preregistered at the Open Science Framework (https://osf.io/89t24/?view_only=d4493dc460934c59bc628f00c2cfa42c).

Participants

We preregistered a sample size of 172 participants in order to achieve a power of $(1 - \beta) = .90$ and medium effect sizes of $f = 0.25$. Due to the outbreak of Covid-19, we had to pause data collection before achieving this preregistered sample size and can now only report data of $N = 133$ participants (101 female, 31 male, 1 diverse; 18 – 39 years old, $M_{\text{age}} = 24.04$, $SD_{\text{age}} = 3.81$). As preregistered, we excluded one participant due to a too low working memory capacity in the Corsi Blocks Task, five participants due to a low performance in the secondary N-back Task (sensitivity/d’ < 0.5), two participants due to missing data and one participant because of not complying with the task instructions. The participants received a financial compensation or course credits for their participation. Data collection will be resumed when the situation allows it again. All participants provided informed consent and the experiment was approved by the ethics committee of the Leibniz-Institut für Wissensmedien.

Apparatus

The participants used a 12.3'' Microsoft Surface Pro tablet (2736 x 1824 pixels) and its touch function to perform a Corsi Blocks Task and the Pattern Copy Task. The tablet laid flat on the table at a viewing distance of approximately 36 cm. To perform to the secondary task (N-back Task), the participants wore headphones for the auditory stimulus presentation and gave answers with a foot pedal. All tasks were presented using PsychoPy (Peirce et al., 2019).

Computer Tasks

The participants performed the tasks in the order they are described.

Corsi Blocks Task. The Corsi Blocks Task measures working memory capacity (adapted from Milner, 1971). In this task, the participants had to observe a spatial sequence and then had to recall this sequence from their working memory. Thus, the participants observed a 5 x 5 grid of empty squares (each 2.52 x 2.52 deg) in which one square after another turned yellow in a 1-second rhythm. After observing the sequence of squares turning yellow and a retention interval of 0.3 seconds, the participants had to recall the sequence by tapping the corresponding squares in the correct order. The task was adaptive, meaning that after a correct recall of a whole sequence the number of squares turning yellow increased by one (with a maximum of 20, but no participant reached this maximal capacity), whereas after an incorrect recall the number squares decreased by one (with a minimum set size of 2). The first sequence started with a set size of two squares turning yellow. The participants performed 30 trials of this Corsi Blocks Task. To calculate working memory capacity, we averaged the set size of the last ten correctly solved trials.

Pattern Copy Task. The Pattern Copy Task is a working memory task that measures cognitive offloading (see also Fu & Gray, 2000; Gray et al., 2006). In this version of the task, the participants had to copy a color pattern of colored squares from a model window into a workspace window (see Figure 10). The participants could either open the model window to observe the pattern by clicking on a bar to its right or open the workspace and resource window to rebuild the pattern by clicking on a bar to its left. Whenever either the model window or workspace and resource window were opened, the other one was covered by a gray mask. The model and workspace window both displayed a 5 x 5 grid of empty squares (each 2.52 x 2.52 deg) whereby the grid in the model window was filled with 12 distinct colored squares (blue, orange, red, cyan, green, dark green, yellow, bisque, sienna, purple, pink, and gray). The resource window included the same twelve colored squares which the participants had to drag and drop into the workspace window.

Within this task I manipulated the temporal costs of cognitive offloading with a no lockout vs. lockout condition. In the no lockout condition the model window opened immediately, whereas in the lockout condition the participants had to wait two seconds first. In the lockout condition the bar that had to be clicked to open the model window turned red for two seconds after clicking. The model window could only be opened after expiration of this two second interval by again clicking onto the bar. This manipulation induced high temporal costs of offloading in the lockout condition whereas the costs of offloading were low in the no lockout condition.

After correctly rebuilding the pattern, the participants could continue with the next trial by pressing an “End Trial” button. When the pattern was not correctly rebuilt, the participants had to keep editing it. The participants performed 20 trials of this task, preceded by two practice trials. The distribution of colored squares within a pattern was randomized to the extent that one participant of each experimental group received the exact same color patterns in the same order. However, due to pausing the study before the whole sample size could be collected, the groups vary in their sample size (see section "Design" for information on group sizes) and thus the equal distribution of patterns is not yet complete. In this task I measured offloading behavior with the following three variables: the number of openings of the model window, the number of correctly copied items after the first opening of the model window and the duration of the very first opening of the model window. A higher number of openings and a lower number of correctly copied items as well as a shorter duration of the first opening indicate more cognitive offloading and thus less internally memorized information.

N-back Task. Simultaneously to performing the Pattern Copy Task, an auditory N-back Task was presented (adapted from Jaeggi et al., 2010; see Figure 10). For all participants the stimuli of the auditory N-back Task were played via headphones during the Pattern Copy Task. Importantly, only half of the participants had to actually perform the task (i.e. react to it; secondary task condition) whereas the other half of participants only listened to it while not being instructed to react to it (no secondary task condition). When starting a trial of the Pattern Copy Task a male voice began to present a random sequence of German consonants (c, g, h, k, p, q, t, w)[12]. Every three seconds a new consonant was presented. Each time when the presented consonant was the same one as the one presented two position before (i.e. 2-back task) the participants in the secondary task condition had to press the foot pedal. They were asked to

[12] Retrieved from https://de.wikipedia.org/wiki/Datei:German_alphabet-2.ogg.

answer as fast and as accurate as possible. The sequence ended when a Pattern Copy Task trial was completed and a new sequence started when a new trial began.

With a chance of 33%, an auditory stimulus was a target (i.e. the participants had to react as the same stimulus occurred 2 stimuli back as well). The stimuli were completely randomized to the extent that no 1-back and 3-back compilations were allowed. To analyze the performance in this secondary task for participants in the secondary task condition, I excluded the last auditory stimulus of each trial and responses with a response time below 0.2 seconds. If a participant reacted to a single stimulus more than once, only the first reaction to this stimulus was analyzed. As proxies of secondary task performance, I then calculated the sensitivity (d') across all 20 test trials and the response time for accurate responses averaged across the 20 trials. The sensitivity (d') was calculated based on the signal detection theory (Macmillan & Creelman, 2004). Accordingly, we performed standard corrections for hit rates of H = 1 (reducing the hit rate by 0.5) and false alarm rates of FA = 0 (increasing the false alarm rate by 0.5). A higher sensitivity as well as shorter response times indicate a higher secondary task performance.

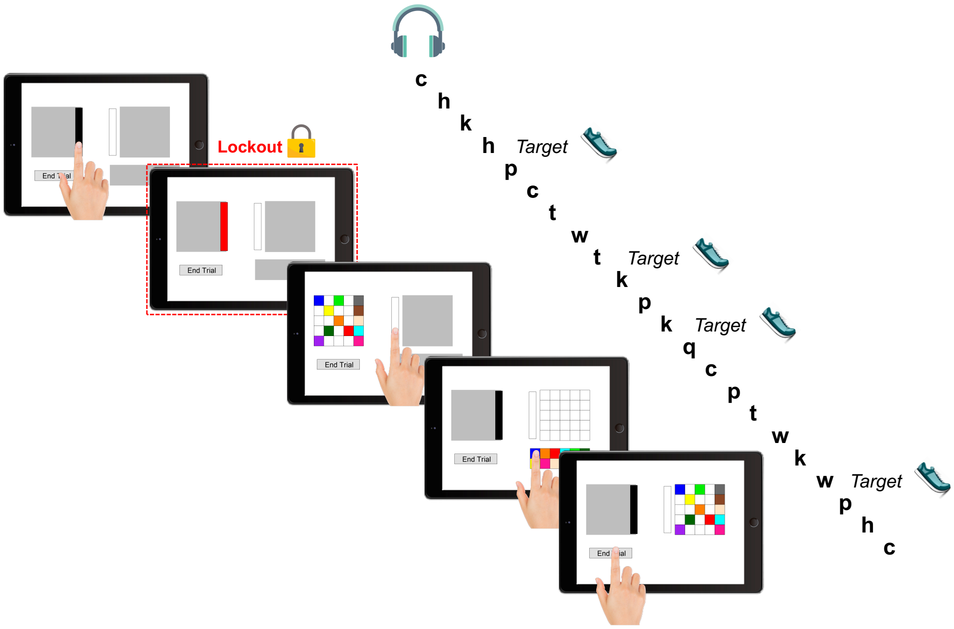

Figure 10. Illustration of the Pattern Copy Task and the simultaneous N-back Task. In the Pattern Copy Task, the participants had to copy a color pattern from a model window into a workspace window. For half of the participants (lockout condition) the opening of the model window resulted in a delay of two seconds, whereas for the other half of participants the model window could be opened immediately (no lockout condition). This task measured offloading behavior. Simultaneously in the N-back Task the participants listened to an auditory presentation of consonants in a three-second rhythm. Half of the participants (secondary task condition) had to react via a foot pedal when the presented stimulus was the same as the one two positions back to measure secondary task performance. The other half of participants (no secondary task condition) did not react to the stimuli. (Lock and headphones designed by rawpixel.com/Freepik; shoe designed by macrovector/Freepik.)

Paper and Pencil Tasks

NASA-TLX. Following the completion of the Pattern Copy Task and the N-back Task, the participants answered the NASA-TLX questionnaire (Hart & Staveland, 1988; Hart, 2006). This questionnaire aims at measuring the workload participants experienced when performing a task or multiple simultaneous tasks. The participants were asked to rate the following variables on a scale from 1 to 21 (very low to very high): mental demand, physical demand, temporal demand, effort, frustration, and performance (perfect performance to failure). As an index of overall workload, I averaged the rating to those questions for each participant.

Self-reported Offloading-Strategies. After answering the NASA-TLX questionnaire, the participants were questioned about the strategy they applied to solve the Pattern Copy Task. I presented them with the following question: "What strategy did you use to complete the pattern copying task on the tablet device?" accompanied by the response options: "I tried to memorize a lot at once instead of having to take a look more often." or "I tried to take a look more often instead of memorizing a lot at once." (in German; here translated to English for illustration). Therefore, the participants could decide between an internal memory strategy (i.e. memorizing more and offloading less) or an offloading strategy (i.e. offloading more by looking up information more often and memorizing less).

Design

This experiment followed a 2 x 2 between-subjects design (see Figure 11). Within the Pattern Copy Task, the participants either experienced low temporal costs (no lockout condition) or high temporal costs of offloading (lockout condition). Simultaneously an auditory N-back

Task was presented. Half of the participants had to actually perform this task by giving responses with a foot pedal (secondary task condition), whereas the other half did not perform this task (no secondary task condition).

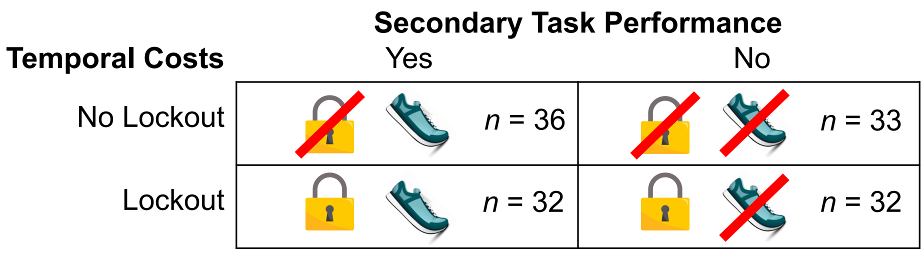

Figure 11. Two by two between-subjects design of the present experiment and sample size of each group. (Lock designed by rawpixel.com/Freepik; shoe designed by macrovector/Freepik.)

Results

Cognitive offloading

To analyze offloading behavior, I performed 2 x 2 between-subjects ANOVAs for each dependent variable of the Pattern Copy Task and the independent variables “temporal costs” as well as “secondary task performance”. Participants in the no lockout condition opened the model window more often, $F(1, 129) = 100.37$, $p < .001$, $\eta_p^2 >= .44$, showed a shorter initial encoding duration, $F(1, 129) = 42.49$, $p < .001$, $\eta_p^2 >= .25$, and copied fewer items correctly at the first opening of the model window, $F(1, 129) = 68.67$, $p < .001$, $\eta_p^2 = .21$, than participants in the lockout condition. Further, also when a secondary task was present the participants opened the model window more frequently, $F(1, 129) = 75.43$, $p < .001$, $\eta_p^2 = .25$, showed a shorter initial encoding duration, $F(1, 129) = 28.82$, $p < .001$, $\eta_p^2 = .14$, and copied fewer items initially correctly, $F(1, 129) = 120.00$, $p < .001$, $\eta_p^2 = .37$, than when no secondary task was present. There was also a significant interaction of the independent variables “temporal costs” and “secondary task performance” with regard to the number of openings of the model window and the initial encoding duration, all *F*s(1, 129) >= 5.01, all *p*s <= .027, all η_p^2s >= .04. Post-hoc *t*-Tests for independent samples showed that with regard to the openings of the model window the presence of the secondary task affected both the no lockout as well as lockout condition, all *t*s >= 6.45, all *p*s < .001, all η_p^2s >= .37, but the difference in means was larger within the no lockout condition than the lockout condition on a descriptive basis (see Figure 12). With regard to the initial encoding duration we observed the opposite pattern, namely a larger differences of means within the lockout condition than the no lockout condition depending on the presence of the secondary task, whereby both comparisons were significant, all *t*s >= -2.89, all *p*s <= .006, all η_p^2s >= .11. Regarding the dependent variable “initially correctly copied items” no significant interaction effect was observed, $F(1, 129) = 3.00$, $p = .086$, $\eta_p^2 = .02$. Thus, across the three offloading variables the interaction effect did not provide a consistent pattern of results. Instead, we consistently observed two main effects showing that the participants offloaded more in the no lockout condition compared to the lockout condition as well as when a secondary task was present compared to when it was absent. Due to its inconsistency the interaction effect will not be further discussed.

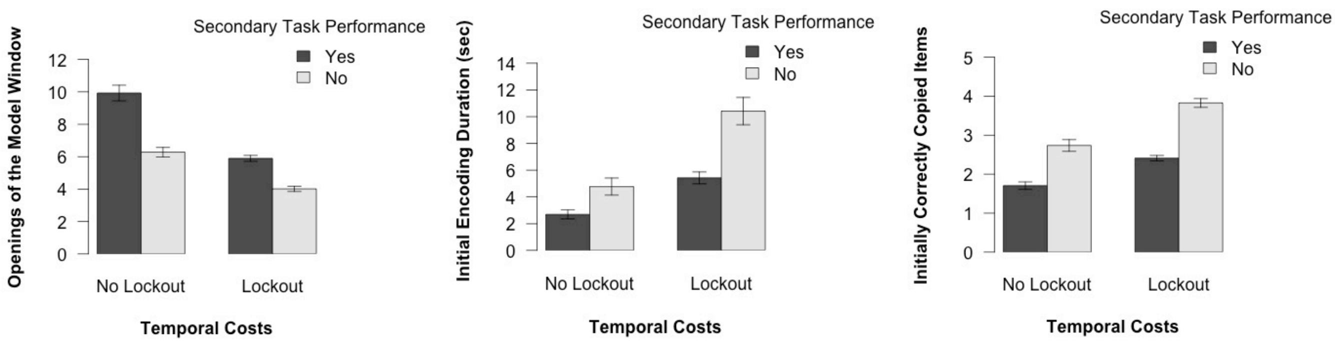

Figure 12. Offloading behavior in the experimental groups. Across all three offloading variables I observed two robust main effects. Error bars present the standard error of the mean.

Secondary task performance

To investigate performance in the secondary N-back Task between the no lockout and lockout condition, we performed two *t*-Tests for independent samples with the dependent variables "response time" and "sensitivity (d')". With regard to response time, we observed no group difference between the no lockout and lockout condition, $t(65.75) = 0.65$, $p = .516$, $\eta_p^2 <= .01$. However, we observed a higher sensitivity (d') in the no lockout condition than in the lockout condition, $t(65.79) = -2.37$, $p = .021$, $\eta_p^2 = .08$ (see Table 17). To investigate whether the lockout manipulation (no lockout/lockout) impacted sensitivity as a measure of secondary task performance directly or whether this relationship is mediated via cognitive offloading, we performed exploratory mediation analyses (see Table 18). We did not observe a mediated effect of the predictor lockout (no lockout/lockout) via cognitive offloading (mediator) on sensitivity, all mediated effects <= -0.16, all *p*s >= .082. Also, the direct effect of the lockout manipulation on sensitivity when taking cognitive offloading into account was not significant, all direct effects <= -0.38, all *p*s >= .122. Thus, solely when taking both predictors into account, neither cognitive offloading nor the lockout manipulation (no lockout/lockout) seems to predict sensitivity as a measure of secondary task performance. For exploratory purposes we also calculated Pearson-correlations between offloading behavior and secondary task performance (see Table 19). Across all variables and groups (except one), we did not observe a correlation between cognitive offloading and response time, all $|rs| <= .34$, all *p*s >= .044, as well as between cognitive offloading and sensitivity, all $|rs| <= .22$, all *p*s >= .019. The exploratory mediation analyses as well as correlations suggest that cognitive offloading is not driving secondary task performance, however, it should be noted that due to pausing our study the analyses are based on a reduced sample size and thus our intended power is not yet achieved.

Table 17. *Means and Standard Deviations of Independent Variables in the Secondary N-back Task and the Corsi Blocks Task*

	No Lockout		Lockout	
	Secondary Task	No Secondary Task	Secondary Task	No Secondary Task
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*
Secondary Task Performance:				
Response Time (sec)	1.23 (0.18)	-	1.25 (0.17)	-
Sensitivity (d’)	2.31 (0.78)	-	1.89 (0.66)	-
Working Memory Capacity:				
Corsi Blocks Task	4.90 (0.64)	4.68 (0.76)	4.71 (0.74)	4.66 (0.87)

Table 18. *Mediation Analyses with the Predictor Lockout (No Lockout/Lockout), Mediator Cognitive Offloading and Outcome Sensitivity*

	Sensitivity (d')			
	Mediated Effect	95% CI	Direct Effect	95% CI
Openings of the Model Window	-0.08	[-0.45; 0.31]	-0.33	[-0.88; 0.20]
Initial Encoding Duration (sec)	-0.16	[-0.37; 0.06]	-0.25	[-0.67; 0.19]
Initially Correctly Copied Items	-0.03	[-0.29; 0.23]	-0.38	[-0.84; 0.10]

Note: * $p < .05$, ** $p < .01$, *** $p < .001$; all mediation analyses were conducted with a bootstrapping procedure (1000 simulations) using the package "mediation" in R (Tingley et al., 2014).

Table 19. *Pearson-Correlations between Cognitive Offloading and Secondary Task Performance*

	Cognitive Offloading	
	Openings of the Model Window	
	Secondary Task	
	No Lockout	Lockout
Secondary Task Performance:		
Response Time (sec)	.13	-.17
Sensitivity (d')	.08	.01
	Initial Encoding Duration (sec)	
	Secondary Task	
	No Lockout	Lockout
Response Time (sec)	.34*	.27
Sensitivity (d')	-.22	-.15
	Initially Correctly Copied Items	
	Secondary Task	
	No Lockout	Lockout
Response Time (sec)	-.11	.06
Sensitivity (d')	.01	-.13

Note: * $p < .05$, ** $p < .01$, *** $p < .001$

Working memory performance

As an indicator of working memory performance, the participants performed the Corsi Blocks Task at the beginning of the experiment. A 2 x 2 between-subjects ANOVA with the independent variables "temporal costs" and "secondary task performance" showed no significant main effects or interaction, all *F*s(1, 129) <= 1.14, all *p*s >= .288, all η_p^2s <= .01. Thus, the experimental groups did not differ in working memory capacity (see Table 17).

Overall workload (exploratory)

To investigate the perceived overall workload of participants measured by the NASA-TLX questionnaire we performed an exploratory 2 x 2 between-subjects ANOVA. Participants in the no lockout condition perceived the performance of the tasks as less demanding than participants in the lockout condition, $F(1, 129) = 13.06$, $p < .001$, $\eta_p^2 = .09$ (see Figure 13). Further, participants not performing a secondary task perceived the task performance as less demanding than participants performing a secondary task in addition to the Pattern Copy Task, $F(1, 129) = 38.10$, $p < .001$, $\eta_p^2 = .23$. There was no interaction effect, $F(1, 129) = 0.14$, $p = .704$, $\eta_p^2 < .01$.

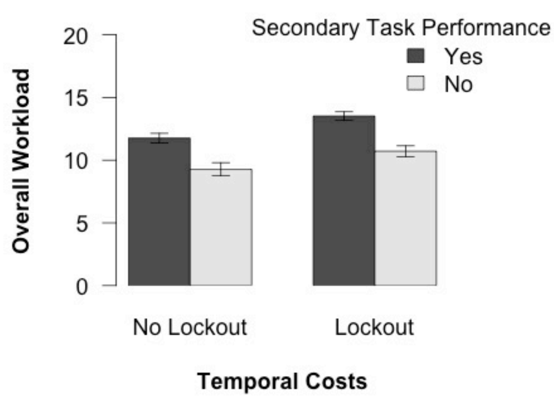

Figure 13. Two main effects of perceived overall workload. Error bars present the standard error of the mean.

Offloading Strategies (exploratory)

At the end of the experiment the participants were asked to indicate the strategy they used to perform the Pattern Copy Task (see Table 20). They could choose an offloading strategy (i.e. relying more on cognitive offloading than one's internal memory) or an internal strategy (i.e. relying more on one's internal memory than offloading). One participant that indicated both strategies was excluded from this exploratory analysis ($N = 132$). To analyze the difference in the selected strategies across the experimental groups we used a logistic regression and the Anova-function of the car package (Fox & Weisberg, 2019). We observed two significant main effects. Participants in the no lockout condition were more likely to choose an offloading strategy over an internal strategy than participants in the lockout condition, $X^2(1) = 4.95$, $p = .026$, $d = 0.39$. Further, participants that performed a simultaneous secondary task were more likely to choose an offloading strategy over an internal strategy than participants not performing a secondary task, $X^2(1) = 21.66$, $p < .001$, $d = 0.89$. This finding suggests, that the participants' reported strategy selection displayed actual offloading behavior. There was no interaction effect between the two independent variables, $X^2(1) = 0.54$, $p = .460$, $d = 0.13$.

Table 20. *Participants per Group That Indicated Either Using an Offloading Strategy or an Internal Strategy to Perform the Pattern Copy Task*

	No Lockout		Lockout	
	Secondary Task	No Secondary Task	Secondary Task	No Secondary Task
	N	*N*	*N*	*N*
Offloading Strategy	33	22	28	13
Internal Strategy	3	10	4	19

Discussion

In the present study we tackled the potential influence of released cognitive resources due to cognitive offloading on the performance of a simultaneous secondary task. Therefore, the participants performed the Pattern Copy Task while either experiencing low temporal costs (no lockout condition) or high temporal costs (lockout condition). Furthermore, they either simultaneously performed a secondary N-back Task or did not perform such a secondary task. The participants offloaded more within the Pattern Copy Task in the no lockout compared to the lockout condition. Beyond this replication of previous findings (see Chapter 4 and e.g., Fu & Gray, 2000; Gray et al., 2006), we also observed an effect of the presence of a secondary task on offloading behavior. The participants offloaded more when a secondary task was present compared to when there was no secondary task. While not observing group differences in response times in the secondary task, participants showed a better secondary task performance in terms of sensitivity in the no lockout than the lockout condition. Thus, our confirmatory analysis suggest that more offloading in the no lockout condition enhanced secondary task performance compared to less offloading in the lockout condition. Released cognitive resources due to offloading in the Pattern Copy Task might thus have been redirected to the simultaneous performance of the secondary task. However, additional exploratory analyses did not support this assumption. The influence of the no lockout/lockout manipulation on sensitivity was not mediated via cognitive offloading in the Pattern Copy Task, nor was cognitive offloading correlated with secondary task performance. Also, the direct effect of the no lockout/lockout manipulation on sensitivity was not significant when taking cognitive offloading into account. Based on these exploratory analyses it remains unclear what actually drives secondary task performance. We will discuss two possible explanations for this discrepancy between the confirmatory and exploratory analyses.

On the one hand, we have to consider that cognitive offloading does indeed not impact secondary task performance (as suggested by the exploratory analyses). Thereby the question arises what drives secondary task performance – if not offloading behavior. With our study we cannot provide any data that would illustrate the driving factor for secondary task performance. However, please note that due to pausing our study the reported results are not based on our intended sample size and statistical power. Our results might be different after finishing data collection. Beyond the present study, we propose to perform further studies that focus, for instance, on the direct effect of the no lockout/lockout manipulation on secondary task performance. Rather than cognitive offloading factors related to the task properties or participants' individual abilities such as working memory capacity might have caused the group difference in secondary task performance within our confirmatory analysis.

On the other hand, the conflicting results emerged from the confirmatory and exploratory analyses might stem from a lack of reliability in the used measures. The maximum correlation between two variables of interest is determined by the reliability of each measure (Danner, 2015). Thus, a prerequisite to observe correlational effects between offloading behavior and secondary task performance is the reliability of the used measures. As we did not test the reliability of the measures in the Pattern Copy Task as well as the N-back Task, we cannot verify this prerequisite for observing correlational effects. It is indeed possible that offloading behavior drives secondary task performance, but that our measures were not reliable enough to detect a correlational relationship within our exploratory analyses.

Retaining the assumption of our confirmatory analyses (i.e. cognitive offloading is driving secondary task performance), we can extend previous findings on the use of released cognitive resources due to cognitive offloading. While Runge et al. (2019) showed that released resources due to offloading can be used for the subsequent performance of an unrelated task, our study suggests that this is also possible when an unrelated task is performed simultaneously. Thus, the saving-enhanced performance effect might also apply to simultaneous task processing. In a similar vein, studies on gesturing as a form of cognitive offloading showed that gesturing while solving a cognitive task releases internal cognitive resources which can be used for the simultaneous memorization of relevant information (Goldin-Meadow et al., 2001; Wagner, Nusbaum, & Goldin-Meadow, 2004). Thus, cognitive offloading seems to improve memory performance for other information through released internal cognitive resources (Goldin-Meadow et al., 2001; Wagner et al., 2004; Storm & Stone, 2015) but also to increase sequential (Runge et al., 2019) as well as simultaneous task processing.

Based on these findings, cognitive offloading might be beneficial for situations that require multitasking (i.e. the performance of multiple tasks at once). Multitasking is highly distributed in everyday life (Colom, Martinez-Molina, Shih, & Santacreu, 2010) as well as in work settings (Appelbaum, Marchionni, & Fernandez, 2008; Kirchberg, Roe, & Van Eerde, 2015). Working memory capacity predicts the simultaneous performance of multiple tasks (Colom et al., 2010), thus lowering working memory demands by offloading working memory processes might facilitate multitasking. In turn, offloading might also decrease psychobiological stress induced by multitasking. Studies showed that multitasking increases psychobiological stress reactivity such as heart rate and blood pressure (Wetherell & Carter, 2013). If cognitive offloading decreases cognitive demands in multitasking scenarios, also the related stress-level might be reduced. Nonetheless, while the present research focused on the positive consequences of cognitive offloading on unrelated task processing, cognitive offloading is also known to have negative consequences especially with regard to the formation of long-term memory representations. Onto this account, studies observed that the offloading of information into technical tools harms subsequent recall performance for this information (e.g., Kelly & Risko, 2019a; 2019b; Sparrow et al., 2011). Therefore, cognitive offloading should be carefully used in different situations in order to achieve the desired outcome. While it might be beneficial when performing multiple tasks at once, it might be harmful when the subsequent recall of information is needed.

Beyond measuring secondary task performance, in the present study we also tested the effects of the experimental manipulations on offloading behavior. The decision to offload working memory processes is known to depend on cost-benefit considerations (e.g., Gray et al., 2006; Risko & Gilbert, 2016; Schönpflug, 1986). When offloading is associated with high costs such as additional time or operational steps, offloading behavior usually decreases compared to when it is associated with low costs. Also, in the present study we can support this assumption by showing more offloading when the associated temporal costs were low (no lockout) compared to when they were high (lockout). In turn, participants in the no lockout condition indicated a lower perceived overall workload (measured by the NASA-TLX questionnaire) than participants in the lockout condition.

Additionally, the participants offloaded more when a secondary task was present than when there was no secondary task. Based on this finding it can be assumed that the Pattern Copy Task and the secondary N-back Task require the same working memory resources. The participants seemed to offload more within the Pattern Copy Task in order to free internal resources for redirecting them to the secondary task performance compared to when no secondary task was present. The assumption that the Pattern Copy Task and the N-back Task fall back onto the same working memory resources supports the view of a central capacity limitation of working memory (Cowan, 2000). Studies using dual task paradigms showed that the concurrent retention of verbal and visual information reduces working memory performance compared to performing a single task, thus suggesting the maintenance of verbal and visual information requires the same working memory resources (Cowan, 2000; Cowan & Morey, 2007). In the present study the presence of a secondary task might thus have increased the load on participants' working memory and therefore enhanced the benefits of an offloading strategy within the Pattern Copy Task. Indeed, although offloading more, the participants performing a secondary task indicated a higher overall workload than participants who did not perform a secondary task. This finding is in line with previous studies suggesting more cognitive offloading when a task includes more information to be processed (Arreola et al., 2019; Gilbert, 2015a; Risko & Dunn, 2015), more complex information (Schönpflug, 1986) or is more difficult (Hu et al., 2019).

The cost-benefit considerations when performing a task might be guided by metacognitive estimations about different strategies, tools, tasks, and one's own abilities (Risko & Gilbert, 2016). While such metacognitive estimations and the related behavior are not always conscious (Efklides, 2008), in the present study we observed that the participants were indeed aware of the strategy they choose to perform the Pattern Copy Task. After performing the Pattern Copy Task, the participants could indicate the strategy they have used to perform this task by choosing either an offloading strategy (more cognitive offloading and less internal memorization) or an internal strategy (less cognitive offloading and more internal memorization). Displaying actual offloading behavior, participants in the no lockout condition were more likely to indicate an offloading strategy over an internal strategy than participants in the lockout condition. Also, participants performing a secondary task were more likely to indicate an offloading strategy over an internal strategy than participants not performing a secondary task. The participants therefore correctly indicated the strategy they have used in the Pattern Copy Task.

To conclude, the present study was the first attempt to test the redirection of released cognitive resources due to the offloading of working memory processes into technical tools on the performance of a simultaneous secondary task. As expected, the manipulation of temporal costs impacted offloading behavior itself as well as secondary task performance. More offloading due to low temporal costs might have increased secondary task performance compared to less offloading due to high temporal costs. Therefore, released resources due to offloading in a working memory task might support the performance of a simultaneous secondary task. However, as the relationship between cognitive offloading and secondary task performance is not yet fully understood, further studies are needed to follow up on this potential relationship.

6. General Discussion

A major restriction of a human's cognitive system arises from limitations in working memory (Baddeley, 2003; Luck & Vogel, 2013). To overcome these strict limitations and to decrease working memory load, individuals can offload working memory processes into their external environment (Risko & Gilbert, 2016; Wilson, 2002). These days, especially modern technical tools such as smartphones and tablets are widely accessible and easily used for cognitive offloading. In the present PhD-project I addressed two lines of research investigating the offloading of working memory processes into modern technical tools. First, I investigated why individuals offload working memory processes. More specifically, I focused on metacognitions that might act as determinants of cognitive offloading. Second, I investigated the consequences of offloading working memory processes through released internal cognitive resources. Importantly, for both lines of research I have used and adapted a free choice offloading paradigm – the Pattern Copy Task (e.g., Fu & Gray, 2000; Gray et al., 2006).

With regard to the first line of research – metacognitions as determinants of cognitive offloading – I performed two studies (Study 1 and Study 2). In the first correlational study I focused on a potential relationship between metacognitions, working memory abilities, and cognitive offloading. I observed that offloading behavior was related to actual working memory abilities. The higher individuals' working memory capacity was, the less they offloaded. However, I did not observe the expected relationship between metacognitive beliefs and offloading behavior. More positive beliefs about one's working memory abilities did not relate to less cognitive offloading. Further, I did not observe a correlation between actual working memory abilities and metacognitive beliefs about one's working memory. Thus, the participants did not correctly monitor their own working memory abilities (i.e. there was a lack of monitoring accuracy). To further test the influence of metacognitions on cognitive offloading, in the second study I experimentally manipulated participants' metacognitive beliefs about their own abilities with fake performance feedback before they performed the Pattern Copy Task. As expected, fake performance feedback strongly influenced participants' metacognitive beliefs. Participants receiving negative fake performance feedback (i.e. indicating a performance below-average) estimated their upcoming performance within the Pattern Copy Task worse than participants receiving positive fake performance feedback (i.e. indicating a performance above-average; with a control group in the middle). Also, participants who received negative feedback indicated to a larger extent that they have used on offloading strategy over an internal strategy to perform the Pattern Copy Task than participants who received positive feedback. In addition, following negative feedback the participants indicated more negative beliefs about their general memory abilities at the end of the whole experiment. However, although the fake performance feedback strongly influenced participants' self-perception, it did not impact actual offloading behavior within the Pattern Copy Task. In sum, the two studies suggest that metacognitive beliefs about one's working memory do not guide offloading behavior – at least not within the Pattern Copy Task. Instead, actual working memory abilities might act as a strong determinant of cognitive offloading. Individuals might adapt their offloading behavior based on how well they actually perform. Thus, based on metacognitive experiences gained during task performance individuals might decide which strategy to use.

Regarding the second line of research – consequences of cognitive offloading – I conducted two more studies in which I tackled the effects of cognitive offloading on the formation of long-term memory representations (Study 3) as well as on the performance of an unrelated secondary task (Study 4). For both – long-term memory formation and secondary task performance – released internal cognitive resources due to cognitive offloading might play an important role. In the third study I observed a trade-off of cognitive offloading suggesting a better immediate task performance but a worse subsequent memory performance due to the offloading of working memory processes. In two experiments I illustrated such a trade-off in an implicit (i.e. the participants were uninformed about the memory test) as well as explicit learning setting (i.e. when the participants were informed about the memory test). These findings suggest that cognitive offloading is harmful for long-term memory formation and cognitive resources released by cognitive offloading are "lost" rather than used for building strong long-term memory representations. Interestingly, in the third experiment I showed that this assumption is wrong. When participants were forced to offload to a maximum extent but still had the intention to build strong long-term memory representations detrimental effects of cognitive offloading could be counteracted. Thus, in this case the participants were able to use the released cognitive resources due to offloading for long-term memory formation. This highlights the importance of an explicit intention to build strong long-term memory representations when offloading working memory processes as negative effects of cognitive offloading on long-term memory could not be counteracted without such an intention.

In the fourth study I tested whether released cognitive resources due to cognitive offloading can be used for the performance of a simultaneous secondary task. Participants performing the Pattern Copy Task with low temporal costs and thus offloading more, showed a better secondary task performance than participants performing the task with high temporal costs and thus offloading less. Cognitive offloading in the Pattern Copy Task might therefore have released internal cognitive resources which could be devoted to the successful performance of the secondary task. Exploratory correlational analyses, however, showed that offloading behavior and secondary task performance were not directly related. Thus, the impact of cognitive offloading and the related released cognitive resources on secondary task performance is not yet fully identified. It is a promising avenue for future research to follow up on the direct impact of cognitive offloading on secondary task performance. In the following sub-chapters I will discuss my findings in the light of previous research, theoretical and practical implications of my studies, their strengths and limitations, as well as future directions.

6.1 The decision to offload working memory processes

Researchers investigating cognitive offloading have identified exogenous factors referring to a person's external environment as well as endogenous factors referring to a person's own internal cognition guiding the decision to offload cognitive processes. Especially metacognitions are supposed to be an endogenous factor that strongly determines the offloading of working memory processes into technical tools (Arango-Muñoz, 2013; Risko & Gilbert, 2016). Earlier studies suggested a negative correlation between metacognitions and offloading behavior (Boldt & Gilbert, 2019; Gilbert, 2015b; Risko & Dunn, 2015; Hu et al., 2019). More positive metacognitive beliefs about one's memory abilities were related to less cognitive offloading. In contrast, within the present PhD-project I did not observe such a relationship. Also, I did not observe a relationship between metacognitive beliefs and actual working memory abilities. While this latter finding is in line with previous studies suggesting that actual abilities predict cognitive offloading independently of metacognitive beliefs (Gilbert, 2015b), other studies suggested that the relationship of actual abilities and cognitive offloading is mediated via metacognitive beliefs (Hu et al., 2019). My findings do not support such a mediating role of metacognitions. The participants in my studies did not show a metacognitive monitoring accuracy (i.e. they did not correctly estimate their own performance; Study 1) neither did metacognitive beliefs predict (Study 1) or causally influence offloading behavior (Study 2). However, higher actual working memory abilities were related to less cognitive offloading within the Pattern Copy Task (Study 1).

To resolve the tension between previous research and the present study regarding the relationship of metacognitions and cognitive offloading the distinction between metacognitive beliefs and metacognitive experiences needs to be considered. On the one hand, metacognitive beliefs (as measured in my studies) reflect offline metacognitive monitoring referring to individuals' general metacognitive knowledge and beliefs about their cognition (Efklides, 2008). On the other hand, metacognitive experiences describe experiences that participants gain while performing a task and therefore are accounted as online metacognitive monitoring (Efklides, 2008). While the former – metacognitive beliefs – seems to strongly affect one's self-perception (e.g., believing that one's memory is unreliable after receiving negative feedback in Study 2), the key factor for guiding the actual control of cognition and thus individuals' selection of specific strategies (e.g., cognitive offloading) might be metacognitive experiences.

In the present studies, I measured participants' metacognitive beliefs before they gained any actual experience of performing the Pattern Copy Task. This method ensured to measure participants' general metacognitive beliefs independent of any actual experience gained when performing a task. However, this method is different to the previous studies observing a correlational relationship between metacognitions and offloading behavior. In these studies, the participants estimated their own performance as an indicator of metacognitions after performing practice trials of the task at hand (Boldt & Gilbert, 2019; Gilbert, 2015b) or after the presentation of the relevant stimuli (Hu et al., 2019; Risko & Dunn, 2015). Thus, in these studies the participants did have actual experiences with regard to the task at hand or the relevant stimuli before providing metacognitive estimations. These metacognitive estimations might therefore reflect metacognitive experiences which in turn seemed to guide offloading behavior in the previous studies.

Similarly, also the participants in my studies might have experienced how good their working memory is while performing the Pattern Copy Task and based on these metacognitive experiences might have adapted their offloading behavior. This would result in a negative correlation between actual working memory abilities and cognitive offloading (Study 1) as well as no group differences in offloading behavior based on fake performance feedback (i.e. the groups did not differ in their working memory abilities and thus did also not differ in offloading behavior; Study 2). Interestingly in my second study I observed that participants' metacognitive beliefs did not coincide with actual behavior (e.g., participants indicated a different strategy to perform the Pattern Copy Task than they actually used). This finding was supported by correlational analyses showing that participants' indication of the used strategy did not correlate with strategy selection (i.e. offloading behavior) following positive and negative fake performance feedback. Thus, there was a discrepancy between metacognitive beliefs and experiences, probably induced by the experimental manipulation of metacognitive beliefs with fake performance feedback. Without a manipulation of metacognitive beliefs in the control group, participants' indication of the selected strategy was indeed correlated with actual strategy selection (i.e. indicating to have used an offloading strategy when actually offloading more). Further, also in the fourth of my PhD-project I observed that the participants were able to correctly monitor the strategy they used to perform the Pattern Copy Task.

Based on metacognitive experiences individuals might consider the costs as well as benefits of an offloading strategy (Arango-Muñoz, 2013; Risko & Gilbert, 2016). For instance, when the costs of offloading are low and the benefit is high (e.g., offloading would increase one's performance when his or her unaided working memory performance is poor within a task) individuals might decide to rely more on cognitive offloading and less on their own internal cognitive processing. With regard to such cost-benefit considerations, my studies also provide insights into exogenous factors, such as temporal costs and the amount of information that needs to be processed, that adaptively guide offloading behavior. Replicating previous studies (e.g., Fu & Gray, 2000; Gray et al., 2006; Patrick et al., 2015; Waldron et al., 2011) the participants offloaded more within the Pattern Copy Task when offloading was associated with low temporal costs than when it was associated with high temporal costs (Studies 3 and 4). This finding supports the *soft constraints hypothesis* suggesting an optimal performance due to the adaptive use of cognitive offloading based on the associated costs and benefits of an offloading strategy (Gray et al., 2006). Less offloading and relying more on one's working memory resources due to high temporal costs was further associated with a higher perceived workload of participants compared to more offloading and relying less on one's working memory due to low temporal costs (Study 4). Reducing the offloading of working memory processes therefore increased the cognitive demands of the task.

In addition, the presence of a secondary task influenced participants' perceived workload and offloading behavior (Study 4). The presence of a secondary task led to a higher perceived workload and more cognitive offloading than when no secondary task was present. This indicates that an auditory secondary task and the Pattern Copy Task actually fall back onto the same working memory resources. When a secondary task was present, there was a high load on participants' working memory resources, thus increasing offloading behavior within the Pattern Copy Task seemed a successful approach to free internal resources for the simultaneous performance of the secondary task. This assumption is similar to prior studies using dual task paradigms to investigate if working memory has a central capacity limitation (Cowan, 2000; Cowan & Morey, 2004). These studies suggest that the simultaneous retention of visual and verbal information draws on the same working memory resources, thus limiting working memory performance compared to single task performance (Cowan & Morey, 2007). In my study, the benefits of cognitive offloading increased due to the presence of a secondary task as did actual offloading behavior. This finding is in line with earlier studies suggesting more cognitive offloading when a task is more effortful and/or difficult due to the processing of more complex information or a larger amount information (e.g., Arreola et al., 2019; Gilbert, 2015a; Hu et al., 2019; Risko & Dunn, 2015; Schönpflug, 1986).

Moreover, also the announcement of an upcoming memory test affected offloading behavior as observed within my studies focusing on the consequences of cognitive offloading for long-term memory formation. In one experiment (second experiment of Study 3) the participants seemed to purposely reduce offloading behavior in order to foster a strong long-term memory when the upcoming memory test was announced. Such a reduction of cognitive offloading when a memory test was announced could be accounted as a self-generated desirable difficulty that serves to foster learning (Bjork & Bjork, 2011). However, I was not able to replicate this finding in the third experiment of Study 3, thus it is not possible to draw strong conclusions regarding participants being metacognitively aware of negative effects of cognitive offloading on long-term memory and in turn purposely reducing offloading behavior.

To summarize, while metacognitive beliefs were not a predictor for offloading behavior in my studies, I argue that metacognitive experiences based on related endogenous factors such as individuals working memory abilities as well as exogenous factors such as temporal costs and amount of information when performing a task guided offloading behavior. Knowledge on such determinants of cognitive offloading is necessary in order to optimally adapt offloading behavior in specific situations. To identify situations in which cognitive offloading can be beneficial or harmful for task performance (and should therefore be adapted), the next sub-chapter deals with the consequences of cognitive offloading on immediate and subsequent task performance.

6.2 Consequences of offloading working memory processes

Due to the ubiquitous availability of technical tools nowadays, working memory processes are easily offloaded in different situations of humans' life. However, cognitive offloading might be accompanied by both – benefits and risks for immediate as well as subsequent task performance. On the one hand cognitive offloading might enable individuals to perform beyond their own internal abilities, but on the other hand the question arises what happens if offloaded information is not available (e.g. during exams or in daily life when the phone's battery dies), thus requiring the internal recall of important information. In the following sections I will discuss the positive and negative consequences of offloading working memory processes on the formation of strong long-term memory representations as well as the performance of unrelated tasks.

6.2.1 A trade-off of benefits and risks of offloading working memory processes

Cognitive offloading is supposed to lower demands on internal cognitive processing and to improve cognition (Kirsh & Maglio, 1994; Risko & Gilbert, 2016). The use of technical tools to offload working memory processes might thus increase immediate task performance but might also affect subsequent cognitive processing. In my PhD-project I illustrated the suggested trade-off of cognitive offloading (Study 3). While cognitive offloading improved immediate task performance within the Pattern Copy Task, it diminished subsequent long-term memory performance for the offloaded information. Cognitive offloading is therefore indeed accompanied by both – benefits and risks on immediate and subsequent cognitive processing. My studies replicated and extended previous research showing a similar trade-off of cognitive offloading when performing the Pattern Copy Task (Morgan et al., 2009; 2013; Waldron et al., 2007). However, in these previous experiments the participants' memory performance was tested immediately after offloading, thus probably not exceeding working memory maintenance. Importantly, in my studies I introduced a longer retention interval until the memory test was performed, thus assuring that memory performance falls back onto long-term memory. In addition, I adapted the Pattern Copy Task depicting more naturalistic offloading behavior using images of daily objects to be copied and memorized instead of colored boxes. With this adapted design I supported the notion of a trade-off of cognitive offloading when offloading working memory processes in a free choice offloading paradigm. This finding is also in line with studies focusing on long-term memory formation after forcing participants to offload. Also, in no-choice paradigms cognitive offloading harmed long-term memory formation (e.g., Eskritt & Ma, 2014; Henkel, 2014; Kelly & Risko, 2019a; 2019b; Sparrow et al., 2011). Thus, across various paradigms both no-choice and free choice offloading behavior increases immediate performance, but also diminishes long-term memory formation for the offloaded information. In other words, relying more on one’s own working memory instead of offloading fosters the formation of strong long-term memory representations. The need of temporarily high loads of working memory to enhance long-term memory formation follows the notion of desirable difficulties. Relying more on one’s working memory instead of offloading makes a task more effortful and can therefore be seen as a desirable difficulty. In turn, this more effortful cognitive processing enhances long-term learning (Bjork & Bjork, 2011). In an incidental learning setting reducing offloading behavior seems therefore a successful attempt to foster long-term memory formation. The observed trade-off of cognitive offloading also follows the framework of Salomon (1990; Salomon & Perkins, 2005) suggesting effects *with* and *of* technology. When interacting *with* technology immediate task processing is enhanced, however, effects *of* technology refer to cognitive residues after technology use such as a reduced long-term memory performance. Nonetheless, in the following section I will discuss why cognitive offloading is not necessarily detrimental for long-term memory under all circumstances.

6.2.2 Positive effects of cognitive offloading on long-term memory through released internal resources

In an incidental learning setting cognitive offloading was harmful for long-term memory formation (Experiment 1 and 2 of Study 3). Nevertheless, the explicit intention to form a strong long-term memory might alter the consequences of cognitive offloading. Cognitive offloading is supposed to release internal cognitive resources (Kirsh, 2010) and these released resources might be used for a deeper processing of the information at hand when individuals have the explicit intention to do so (Craik & Lockhart, 1972; Craik, 2002). Supporting this assumption, I demonstrated that when participants had the explicit intention to foster long-term memory but also had to offload to a maximum extent, they were able to counteract the detrimental effects of offloading (Experiment 3 of Study 3). Thus, under these circumstances the participants were able to use the released cognitive resources due to cognitive offloading in order to enhance long-term learning. Interestingly, the use of released cognitive resources for long-term learning was only observed when the participants were forced to offload to a maximum extent and not when they could freely choose the amount of cognitive offloading – even if the memory test was announced. More offloading under free choice was always related to a worse subsequent memory performance. One reason for the ability to counteract negative consequences of offloading maximally might be the requirement of a certain amount of released cognitive resources. Maximally offloading is supposed to release a maximum amount of internal cognitive resources which might be required for long-term memory formation. On the other hand, offloading at a medium extent under free choice conditions might not release enough internal cognitive resources to build a strong long-term memory. Another reason might be that operating at a medium memory load under free choice conditions is too effortful for using released internal cognitive resources. Further studies are required to investigate the specific mechanisms involved in cognitive offloading that harm or foster long-term memory. Importantly, with an explicit intention to build a strong long-term memory cognitive offloading is not necessarily detrimental for long-term memory formation.

6.2.3 Using released resources due to offloading to perform unrelated tasks

Released resources due to cognitive offloading might also be used for the performance of unrelated tasks. Onto this account, I investigated if cognitive offloading fosters the performance of a simultaneous secondary task (Study 4). While low temporal costs increased offloading behavior compared to high temporal costs it was also accompanied by a better secondary task performance. Thus, as expected more cognitive offloading seemed to foster secondary task performance. Released cognitive resources due to offloading might therefore be instantaneously redirected to successfully perform an unrelated task. However, this interpretation must be treated with caution. Exploratory analyses of my data did not support the assumption of cognitive offloading being the key driver for secondary task performance (e.g., there was no correlation between cognitive offloading and performance in the secondary task). Therefore, it is a promising avenue for future studies to aim at explaining the positive effects of offloading working memory processes on secondary task performance.

Previous studies showed that released cognitive resources due to cognitive offloading in one task (i.e. saving information in a technical tool) can enhance the subsequent performance in an unrelated task (Runge et al., 2019). With my study I can extend this *saving-enhanced performance effect* to the simultaneous performance of a task. Thus, released resources due to offloading might be used to foster not only subsequent cognitive processing but also instantaneous cognitive processing. In addition, released cognitive resources are also known to be beneficial for the memorization of new information (Runge et al., 2020; Storm & Stone, 2015). Due to the offloading of irrelevant information released resources could be used to memorize relevant information. Therefore, the use of released resources due to cognitive offloading also induces a *saving-enhanced memory effect* (Storm & Stone, 2015). In addition, not only offloading into the world (e.g., into a technical tool) supports unrelated task processing or memorization, but also offloading onto the body releases internal cognitive resources which can be used for memorization. Studies investigating gesturing as a form of cognitive offloading when solving mathematical problems illustrated that gesturing releases internal cognitive resources. In turn these released resources could be used for the memorization of relevant information while solving the mathematical problems (Goldin-Meadow et al., 2001; Wagner et al., 2004).

Based on the beneficial effects of cognitive offloading through released internal cognitive resources on unrelated task processing, cognitive offloading might be helpful for multitasking. Multitasking (i.e. performing multiple tasks at once) is highly distributed in work settings (Appelbaum et al, 2008; Kirchberg et al., 2015) as well as in daily life (Colom et al., 2010). Performance in multitasking settings is determined by working memory capacity (Colom et al., 2010). When participants have a higher working memory capacity, they are usually more successful in multitasking. Thus, lowering working memory demands via cognitive offloading might enhance multitasking performance and especially support individuals with a low working memory capacity. In turn, cognitive offloading could also serve to decrease psychobiological stress induced by multitasking. Multitasking is known to increase individuals' stress-level as indicated by mood, heart rate, and blood pressure, for instance (Wetherhell & Carter, 2013). Due to offloading, multitasking performance could be enhanced while also lowering the related psychobiological stress-level.

6.3 Theoretical implications

In their review on cognitive offloading Risko and Gilbert (2016) introduced a *metacognitive model of cognitive offloading*. This model claims that lower-level cognitive processes such as one's memory abilities influence individuals' metacognitive beliefs and experiences. Both metacognitive beliefs and metacognitive experiences then guide the metacognitive evaluation of different strategies such as relying on internal memory or cognitive offloading. Based on this evaluation individuals decide which strategy to use for task performance. In turn, the use of a specific strategy such as offloading is supposed to directly influence future metacognitive beliefs and experiences but also lower-level cognitive processes such as one's memory. Thus, it is assumed that cognitive offloading is accompanied by long-term consequences on internal cognitive processing. Together, the metacognitive model of cognitive offloading claims a circuit of lower-level cognitive processes influencing metacognitions and in turn offloading behavior, whereby then the selection of a specific strategy (i.e. cognitive offloading) affects future metacognitions as well as lower-level cognitive processes.

A central advantage of the present PhD-project was the use of one offloading paradigm – the Pattern Copy Task – to investigate both, determinants and consequences of cognitive offloading. Therefore, I can combine the findings of my studies to evaluate the metacognitive model of cognitive offloading (Risko & Gilbert, 2016). First, I observed that offloading behavior within the Pattern Copy Task is determined by individuals' working memory abilities and task properties. Therefore, as suggested by the metacognitive model of cognitive offloading lower-level cognitive processes such as individuals' memory abilities indeed predicted offloading behavior. However, the present studies do not support the claim that metacognitive beliefs influence cognitive offloading. Rather metacognitive experiences gained during task performance with regard to one's working memory abilities and/or task properties might influence the metacognitive evaluation of costs and benefits of an offloading strategy and further impact strategy selection. In turn, the decision to offload working memory processes had consequences for immediate and subsequent task processing. On the one hand, cognitive offloading accelerated immediate task performance in the Pattern Copy Task and fostered performance in an unrelated secondary task. Thus, cognitive offloading had positive immediate consequences within my studies. On the other hand, cognitive offloading negatively affected individuals lower-level cognitive processes (measured as long-term memory performance). The participants showed a reduced long-term memory performance for offloaded information within my studies. This finding supports the metacognitive model of cognitive offloading by showing that the use of an offloading strategy indeed affects subsequent cognitive processing. As suggested by Risko and Gilbert (2016), if individuals then experience a poor memory for specific information, they might metacognitively evaluate their internal abilities as unreliable and in turn keep relying on cognitive offloading. In sum, my studies mostly provide support for the metacognitive model of cognitive offloading when systematically investigating the offloading of working memory processes with the Pattern Copy Task. Only with regard to the influence of metacognitive beliefs on offloading behavior my studies cannot support this model.

The lack of metacognitive beliefs influencing cognitive offloading raises two important questions. First, it raises the question whether a more differentiated metacognitive model of cognitive offloading is needed. On the basis of previous research, I would suggest metacognitive experiences as a key driver for cognitive offloading, however, the potential influence of metacognitive beliefs on offloading behavior needs further investigation. Most importantly, it appears necessary to disentangle the effects of metacognitive beliefs and metacognitive experiences on offloading behavior instead of assuming that metacognitions are a general driver for cognitive offloading.

Second, beyond the differentiation of metacognitive beliefs and experiences, also general differences in the administered paradigms to measure cognitive offloading need consideration. While previous studies indeed observed a relationship between metacognitions and cognitive offloading in, for instance, a prospective memory task (e.g., Boldt & Gilbert, 2019; Gilbert, 2015b), my studies could not support these findings. These conflicting results might arise from the different offloading paradigms used and thus from different forms of cognitive offloading. For instance, within a prospective memory task (e.g., Gilbert, 2015b) the participants could offload future intentions whereas within the Pattern Copy Task the participants offloaded by instantaneously looking up relevant information. These two forms of offloading behavior – intention offloading and offloading in the Pattern Copy Task – might be different per se, thus they might also be driven by different determinants. The offloading of future intentions might be related to more planning before action and thus be guided by metacognitive beliefs whereas offloading in the Pattern Copy Task might be related to ongoing cognitive processing during the task. However, no study has directly compared these different forms of cognitive offloading. Therefore, it is a promising direction for future research to compare different offloading paradigms and related factors such as determinants and consequences of cognitive offloading in each paradigm. Such investigations would help to further evaluate the metacognitive model of cognitive offloading that does not take different forms of cognitive offloading into account so far.

Another relevant theory for the present project is the proposed *extended selection problem* by Arango-Muñoz (2013). Individuals often have to decide whether or not to externalize cognition into technical tools which raises the extended selection problem. Arango-Muñoz (2013) describes metacognitions as an experience-based control system that guides this decision (and thus solves the extended selection problem). Similar to Risko and Gilbert (2016), he proposed that individuals metacognitively evaluate the costs and benefits of different strategies to perform a task. These metacognitive evaluations often induce metacognitive feelings that guide strategy selection such as relying on one's own cognitive processing or offloading cognition into the technical tool at hand. This theory follows my suggestion of metacognitive experiences with regard to one's internal abilities and/or task properties influencing offloading behavior. Interestingly, individuals are not always aware of their metacognitive evaluations and related strategy selection. Metacognitive trainings might increase individuals' consciousness about their metacognitive processes and thus optimize strategy selection. I will further discuss this idea in the following sub-chapter.

6.4 Practical implications

Humans offload cognitive processes into technical tools in various situations of their life. Cognitive offloading is present in work contexts, educational contexts, as well as in daily routines. Importantly, cognitive offloading comes along with both – benefits and risks; thus, using cognitive offloading as a strategy to perform tasks should be treated with caution. In some situations, cognitive offloading might be beneficial, whereas in other situations it might be harmful depending on the present goal. In order to reach one's goal it is therefore necessary to adaptively use cognitive offloading. In situations that require an optimal immediate task performance, cognitive offloading is recommendable as it is known to improve immediate task performance. For instance, in working contexts individuals might rely on a technical tool rather than their internal cognitive processing when a task needs to be performed quickly and without any errors. Onto this account, a cashier might use a calculator instead of doing mental arithmetics or a waiter/waitress might write down an order instead of memorizing it. Also, when performing multiple tasks at once (i.e. multitasking) cognitive offloading in one task might be beneficial for the performance of another task. For instance, an individual might be on the phone listening to a friend while also planning the next trip to the grocery store. This individual might be able to pay more attention to his or her friend on the phone when he or she writes down the groceries he or she needs to buy later than when trying to memorize them. In these examples cognitive offloading can be used for an optimal task performance, however, in other situations individuals should reduce offloading behavior. Cognitive offloading is known to harm the formation of long-term memory. Thus, if the later recall of information is necessary and then a technical tool is not available to retrieve the relevant information, one should rather rely on internally memorizing important information instead of offloading it. For instance, in an educational context, individuals should try to memorize relevant information instead of storing it into technical tools as this information should be recalled from memory in situations in which technical tools are not available (e.g., during exams). Nevertheless, if individuals have the goal to foster long-term learning and offloading cannot be avoided, they might still be able to form a strong long-term memory. This highlights the importance of an explicit intention to foster learning when using technical tools.

After identifying situations that require more or less cognitive offloading, the proper strategy needs to be selected in order to maximize performance. I propose two approaches that might support individuals' strategy selection. On the one hand, individuals might be metacognitively trained to properly estimate their own performance and to know the benefits and risks of an offloading strategy. Onto this account, Gilbert et al. (2020) showed that participants usually offload more than is optimal for their performance. This bias towards cognitive offloading could be eliminated by providing the participants with metacognitive advice on the effectiveness of offloading. Similarly, Ghatala (1986) showed that metacognitive training supports the successful strategy selection of children. Furthermore, knowledge about one's internal cognitive abilities can enhance optimal strategy selection. Individuals are often overconfident with regard to their performance but providing participants with performance feedback can increase their metacognitive accuracy (Callender et al., 2016). If individuals are able to correctly judge their own performance, they might be able to use the proper strategy to perform a task (e.g., more offloading when one's working memory is unreliable). In addition, supervisors in working contexts or teachers might be trained on the benefits and risks of cognitive offloading in order to guide their staff or students to use technical tools successfully.

Another approach to support strategy selection is the implementation of constraints into technical tools that guide the adaptive use of cognitive offloading. A recent study showed that individuals offload more working memory processes into technical tools when the tool is highly responsive and easy as well as intuitive to control (Grinschgl et al., 2020). Thus, in situations that require more cognitive offloading tools could be designed to be highly responsive and easy to use, whereas in situations that require less offloading tools could be designed less responsive and hard to use. Such constraints in tool design are supposed to then guide individuals' offloading behavior (see also Grinschgl et al., 2020; for a discussion of this idea). Thus, knowledge on benefits and risks of cognitive offloading is important for designers creating different applications and tools.

Beyond direct benefits and risks of cognitive offloading, optimizing offloading behavior is also relevant because of some accompanying factors. For instance, studies showed that when individuals interact with external knowledge such as information on the internet, they intermix their own knowledge and this external knowledge (Fisher, Goddu, & Keil, 2015; Hamilton & Yao, 2018; Ward, 2013; Wegner & Ward, 2013). Such illusions of knowledge might lead to a suboptimal performance when external knowledge stored in the internet or in technical tools cannot be accessed. In addition, a recent study showed that participants are vulnerable to manipulations of information stored in technical tools (Risko, Kelly, Patel, & Gaspar, 2019). In this study the participants offloaded information into a technical tool and then the offloaded information was manipulated by the experimenter. The participants rarely noticed this manipulation when retrieving the information from the technical tool. Further, the use of internet to retrieve information as a form of cognitive offloading affects future internet use (Storm et al., 2016). This suggests that extensively offloading in one task leads to more pronounced offloading in another task. All those consequences of cognitive offloading encourage a careful use of cognitive offloading in daily life, work, and educational contexts.

6.5 Strengths, limitations, and future directions

Starting with the strengths of the present PhD-project I would like to highlight its' innovativeness. I did not only follow up on previous findings of offloading research, but I also used innovative methods in order to gain additional insights on humans' offloading behavior. Based on a theory-driven hypothesis generation, I tested metacognitions as determinants of cognitive offloading and consequences of offloading behavior. Therefore, I was able to empirically test the validity of proposed theories such as the *metacognitive model of cognitive offloading* by Risko and Gilbert (2016) with innovative methods such as a manipulation of metacognitive beliefs via fake performance feedback, a long-term memory test for offloaded information, and a dual task approach. While most research on cognitive offloading has either tackled the determinants of cognitive offloading or consequences of offloading, my PhD-project provided a systematic investigation of both factors using one offloading paradigm, thus allowing a combination of my findings. Further, I administered the Pattern Copy Task on tablet devices – aiming at reflecting offloading behavior into modern technical tools. The Pattern Copy Task entails another advantage – the measurement of free choice offloading behavior. Even though many studies on cognitive offloading used a design in which participants were either prohibited from or forced to offload, such a no choice design is rather sub-optimal as it does not reflect real-life offloading behavior. In daily life, individuals can usually decide on their own when and how much cognitive processes to offload. Therefore, using a free choice offloading paradigm such as the Pattern Copy Task allows an investigation of cognitive offloading that is closer to offloading in real-life than using a no-choice paradigm. As another strength of my studies I would like to highlight the large sample sizes that provide a sufficient statistical power. Especially in times of the replication crisis a substantial sample size is important for the interpretation of statistical results. Onto this account, I also point out that all my studies were preregistered with regard to the sample size, exclusion criteria, independent and dependent variables, as well as statistical analyses. All analyses that were not preregistered were marked as "exploratory".

As a limitation of my studies the measurement of metacognitions needs to be discussed. Research on metacognitions classically uses measures such as judgments of learning (e.g., judgments about memory performance on previously learned word pairs) or feelings of knowing (e.g., rating of likelihood to remember specific information; Kelemen et al., 2000; Nelson & Narens, 1990; Schwartz, 1994). However, these classical measures were not transferrable to my studies in which I aimed at measuring how individuals' beliefs about their internal abilities impact offloading behavior. I therefore used subjective performance estimations as an indicator of metacognitive beliefs. As this measurement of metacognitions has not been previously established, I have to consider the possibility that it did not fully depict metacognitive beliefs. Hence, I urge for further studies using different measures to investigate metacognitions in the context of cognitive offloading. Another limitation of the present PhD-project concerns the measurement of long-term memory performance following cognitive offloading. Compared to previous research (Morgan et al., 2009; 2013; Waldron et al., 2007) I significantly increased the retention interval until a memory test was performed. The processing of the relevant information within the Pattern Copy Task and the memory test were separated by two working memory tests taking about 20 minutes. Nevertheless, it would still be interesting to further increase this retention interval in order to investigate consequences of cognitive offloading across longer time frames. I suggest testing memory performance on the following day or even after several days. In my studies such an increased retention interval was not possible due to economic reasons. With large sample sizes of $N = 172$ it was not feasible to test the participants twice on two successive days.

With the Pattern Copy Task, I was able to measure free choice offloading behavior in order to depict offloading behavior in real-life. Nonetheless, the Pattern Copy Task is still a highly experimental paradigm. This is beneficial for systematic empirical investigations but of course might not be fully transferrable to real-life offloading behavior. As a future direction I therefore suggest conducting field studies that focus on cognitive offloading in situations of daily life, classroom settings, or work environments. Due to the proceeding digitalization in schools, students need to interact with technical tools more and more. In some situations, cognitive offloading might be successfully used to support students' performance whereas in other situations it might be harmful. Similarly, cognitive offloading should also be investigated in work environments, especially when employers have the goal to foster their employees' long-term abilities.

As many other experimental investigations, my studies used student samples. However, student samples are often not representative of the whole population (Hanel & Vione, 2016; Rad, Martingano, & Ginges, 2018). Thus, the generalizability of my findings is limited. I assume that the participants in my studies were familiar with working with modern technical tools and thus might have some knowledge on how to successfully administer these tools to reach their goals. Onto this account, Hamilton and Yao (2018) showed that device familiarity modifies individuals' assessment of their personal knowledge. Device familiarity, related knowledge, and offloading behavior might be different when using other samples such as young pupils that just start using technical tools or older adults that did not grow up with technical tools in their daily life. One study testing offloading behavior across a wider age-span showed that offloading behavior is more pronounced in older adults than younger adults (Gilbert, 2015a). I therefore recommend replicating the main findings with regard to determinants and consequences of cognitive offloading with different samples and age-groups. In this regard I also see a high potential of field studies, for instance, in schools that can serve to broaden the knowledge on cognitive offloading as a strategy for task performance.

6.6 Conclusion

In the present PhD-project I systematically investigated the offloading of working memory processes using the Pattern Copy Task. As a first line of research I focused on metacognitions as possible determinants of offloading behavior. I conclude that metacognitions are not a universal predictor for cognitive offloading. Within my studies, metacognitive beliefs about one's internal abilities did not impact the offloading of working memory processes, but I propose that metacognitive experiences might guide cognitive offloading. I urge for a careful distinction between metacognitive beliefs and metacognitive experiences and their differentiated effect on offloading behavior. As a second line of research I investigated the short-term and long-term consequences of offloading working memory processes. I observed that cognitive offloading improves immediate task performance but also diminishes long-term memory performance for the offloaded information. Nonetheless, with an explicit intention to foster a strong long-term memory and no possibility to reduce offloading behavior individuals could counteract the detrimental effects of cognitive offloading. Therefore, internal cognitive resources released by cognitive offloading are not necessarily lost but can be used for long-term memory formation under specific circumstances. Moreover, released cognitive resources due to cognitive offloading might be beneficial for the performance of a simultaneous secondary task. My studies serve for a better understanding of the offloading of working memory processes into technical tools and provide important insights for future research and humans' technology use in daily life.

7. References

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8. Electronic supplementary material for Chapter 4/ Study 3

Scatter Plots for Experiment 1

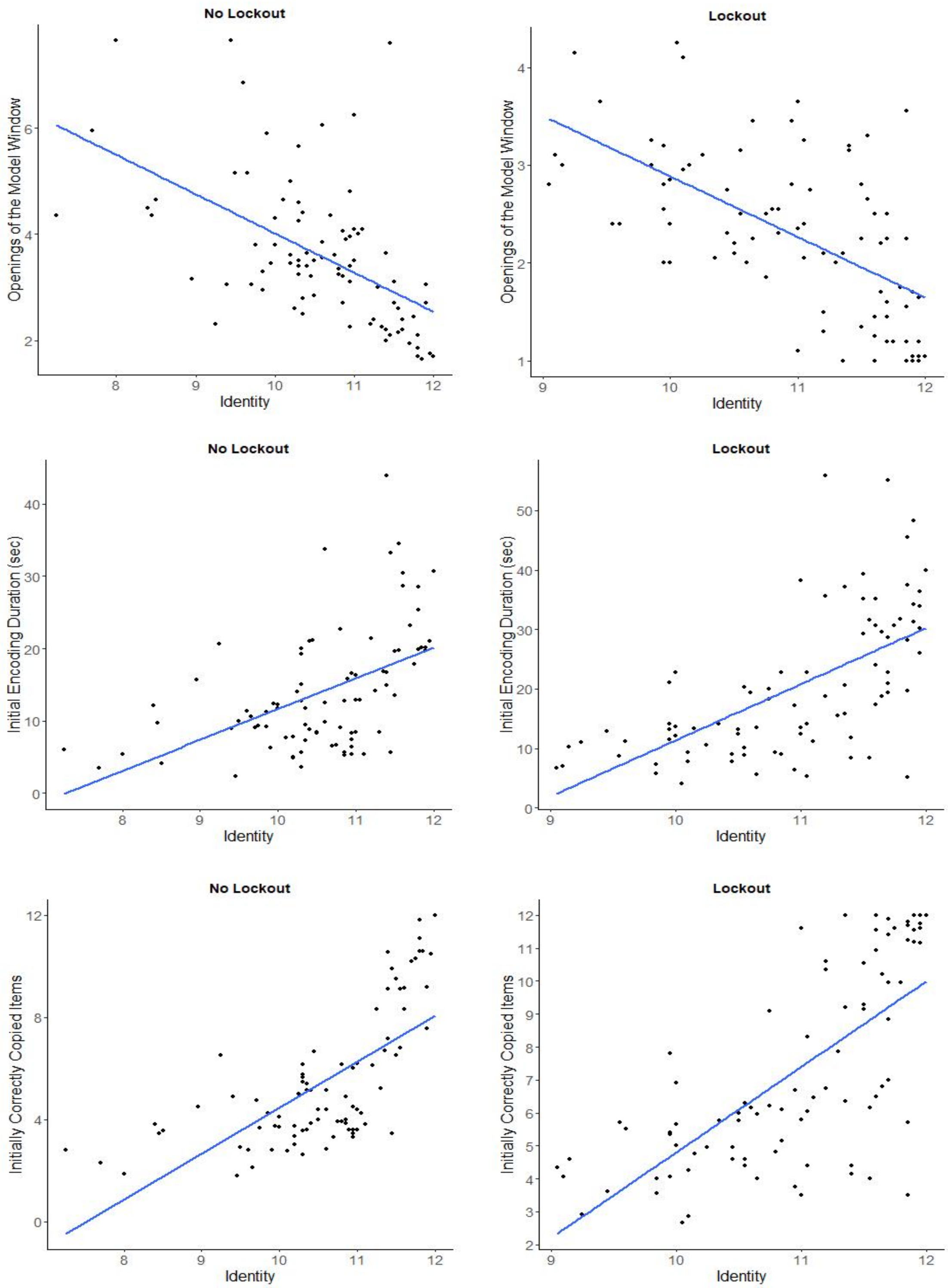


Figure 1.1. Scatter Plots of Correlational Analyses between Cognitive Offloading and Memory Performance (Identity) for Experiment 1 (see also Table 9 in Chapter 4).

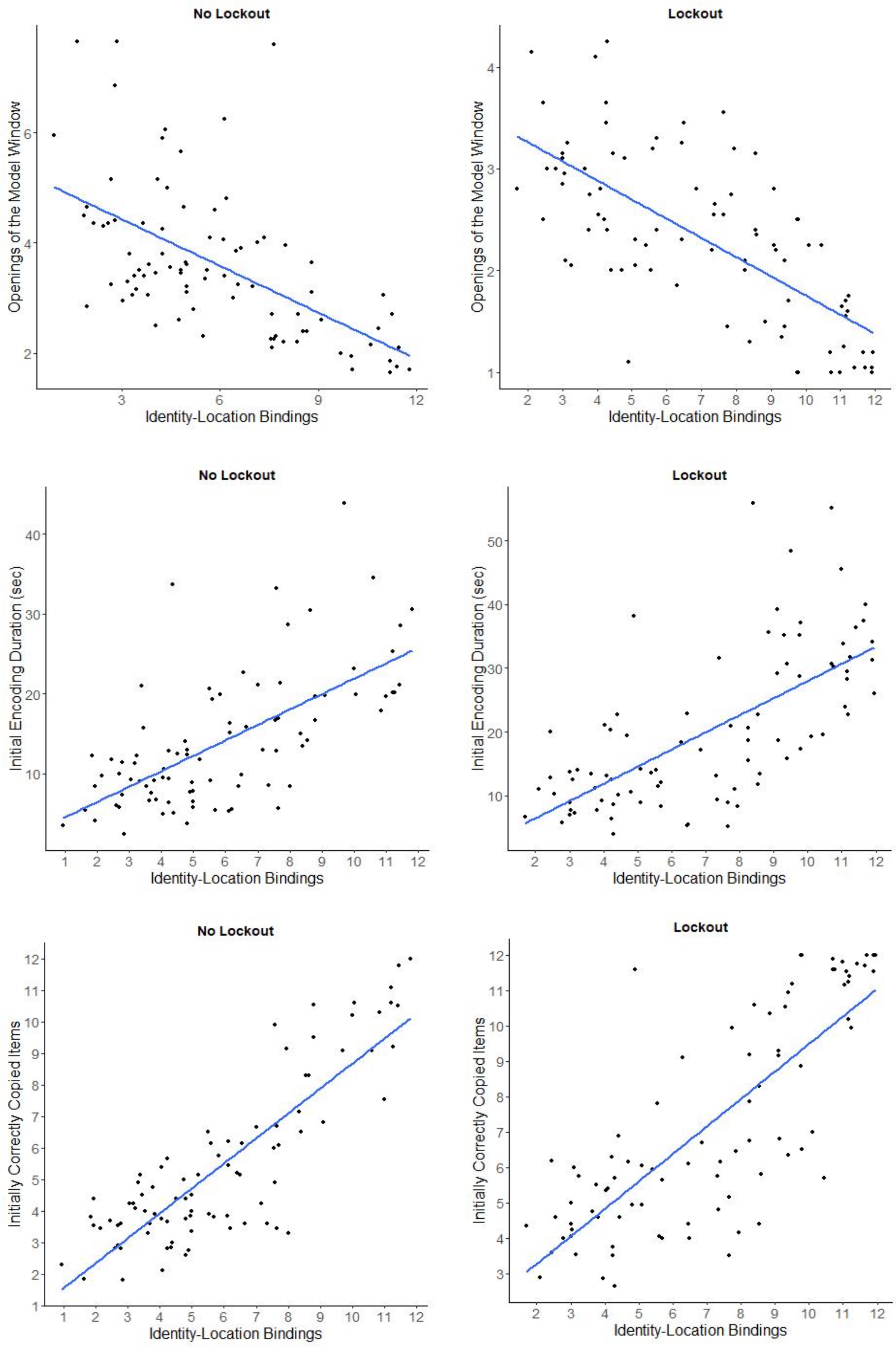


Figure 1.2. Scatter Plots of Correlational Analyses between Cognitive Offloading and Memory Performance (Identity-Location Bindings) for Experiment 1 (see also Table 9 in Chapter 4).

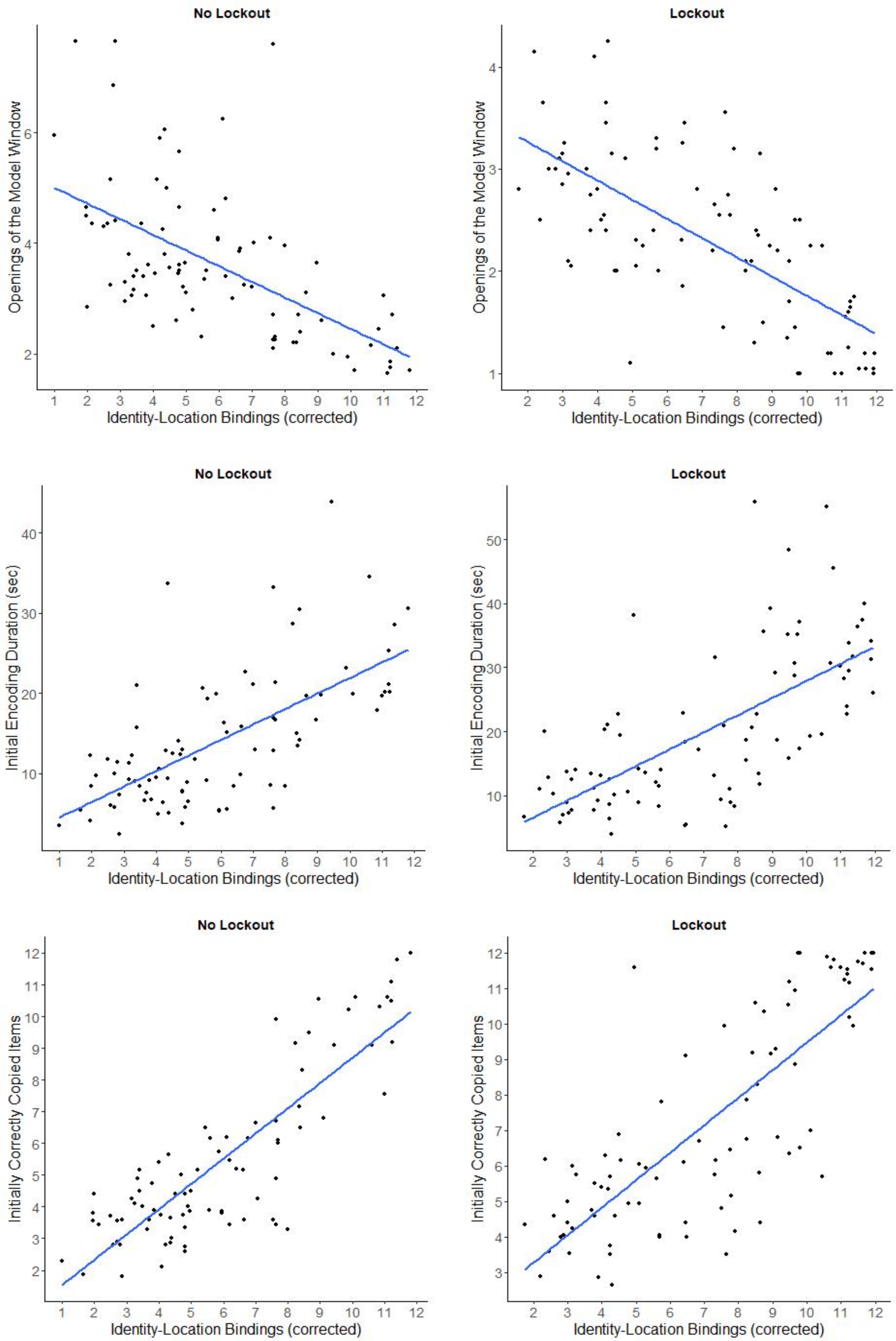


Figure 1.3. Scatter Plots of Correlational Analyses between Cognitive Offloading and Memory Performance (Identity-Location Bindings corrected) for Experiment 1 (see Table 9 in Chapter 4).

Scatter Plots for Experiment 2

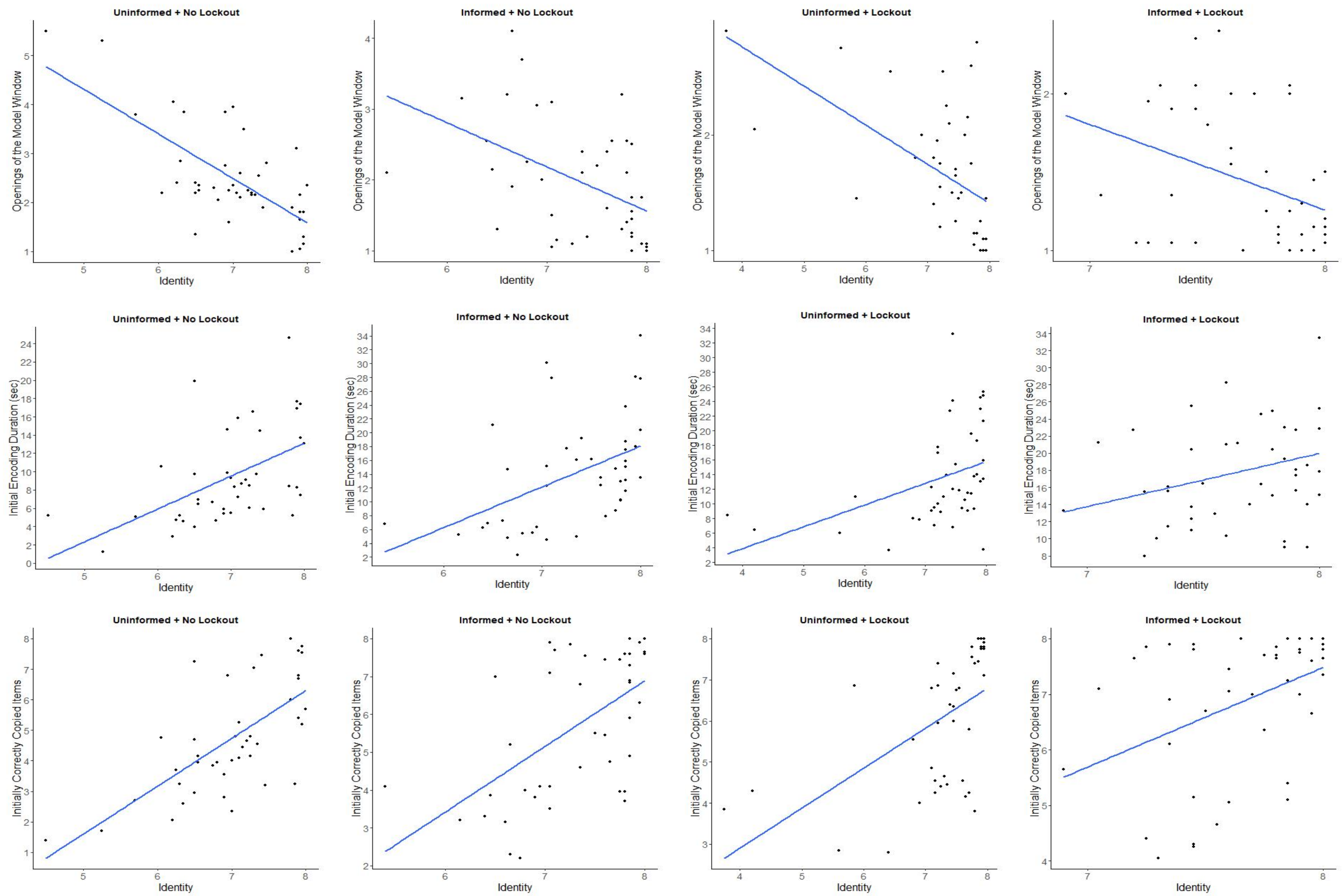


Figure 2.1. Scatter Plots of Correlational Analyses between Cognitive Offloading and Memory Performance (Identity) for Experiment 2 (see also Table 12 in Chapter 4).

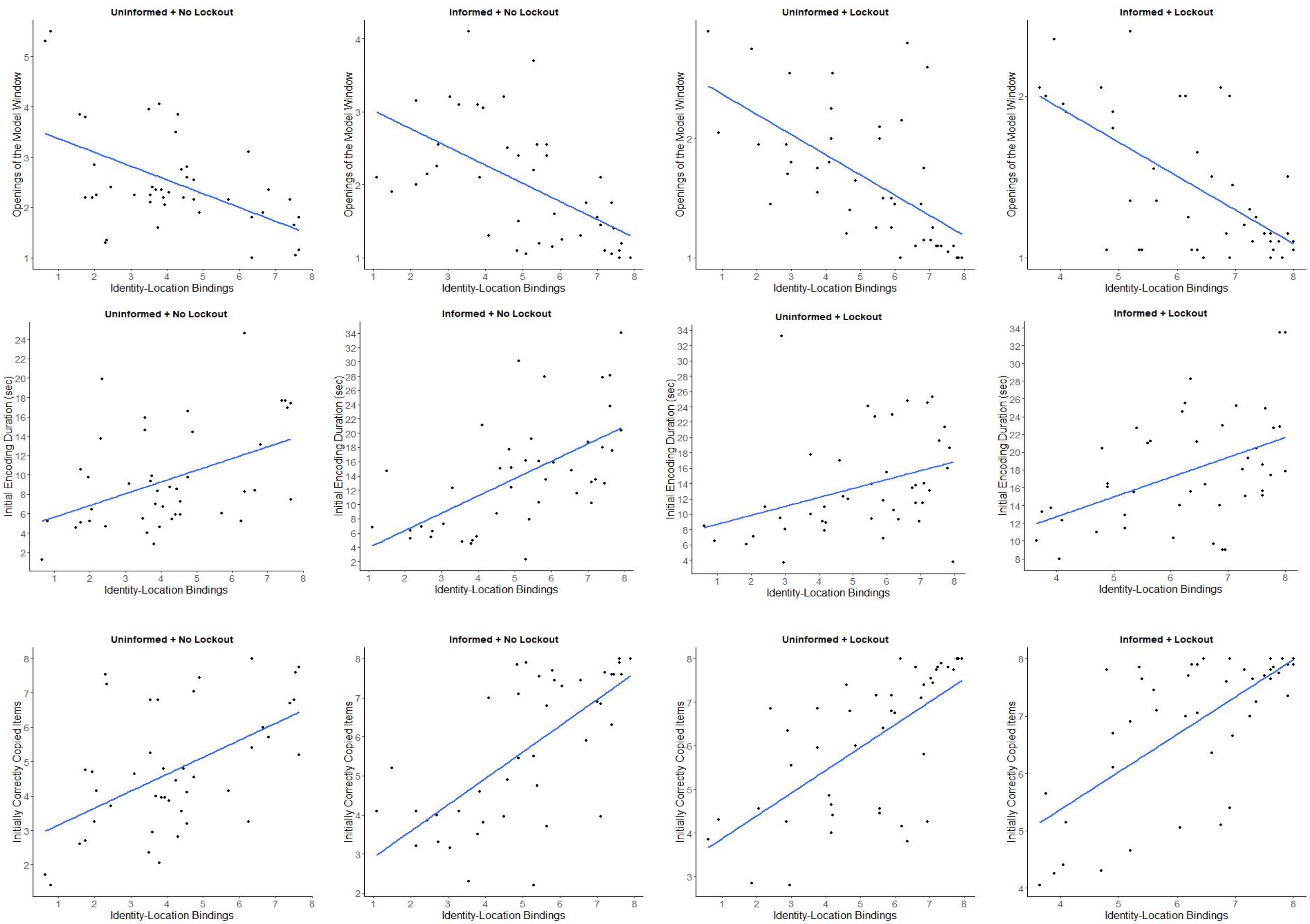


Figure 2.2. Scatter Plots of Correlational Analyses between Cognitive Offloading and Memory Performance (Identity-Location Bindings) for Experiment 2 (see also Table 12 in Chapter 4).

Scatter Plots for Experiment 3

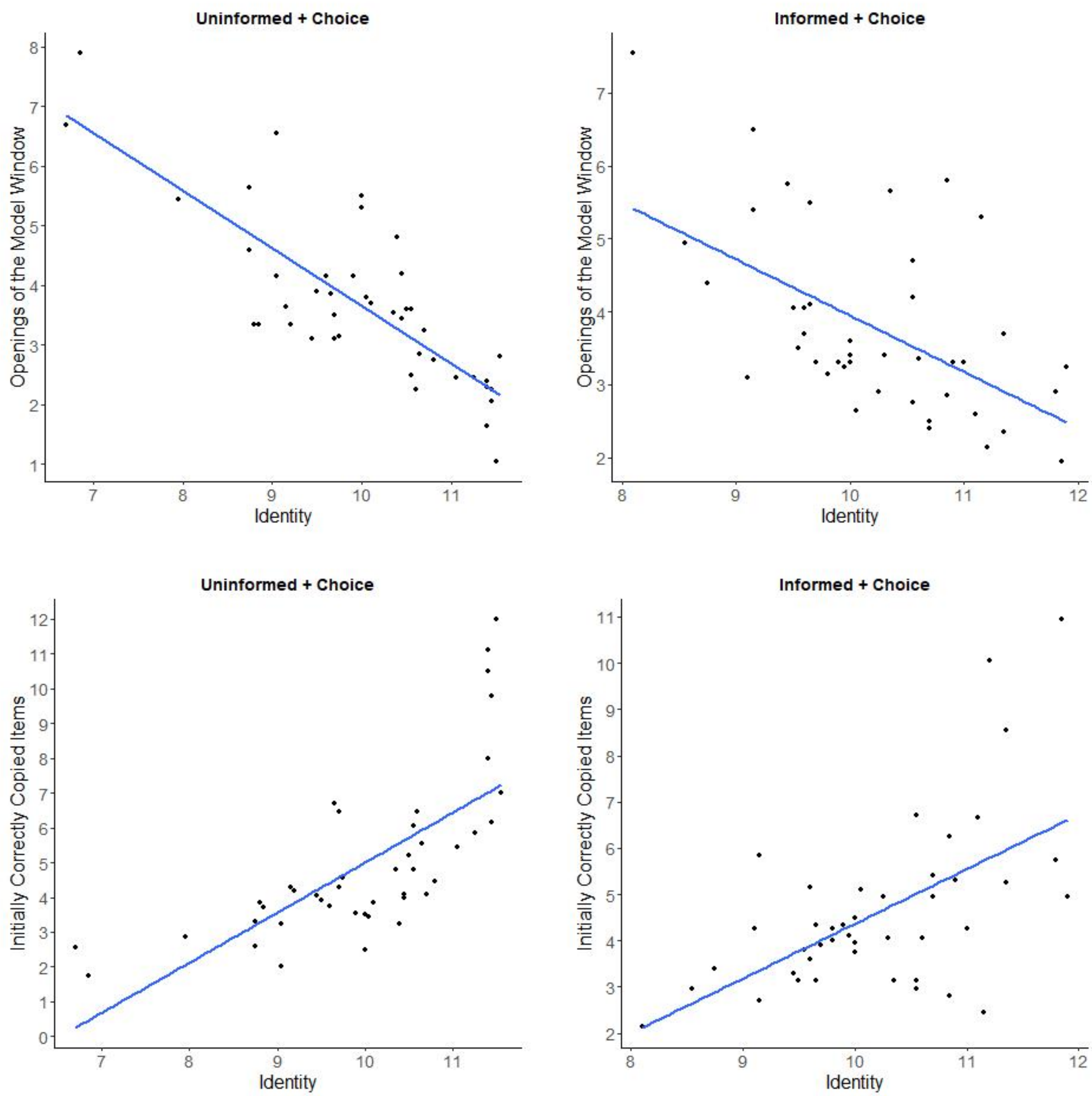


Figure 3.1. Scatter Plots of Correlational Analyses between Cognitive Offloading and Memory Performance (Identity) for Experiment 3 (see also Table 16 in Chapter 4).

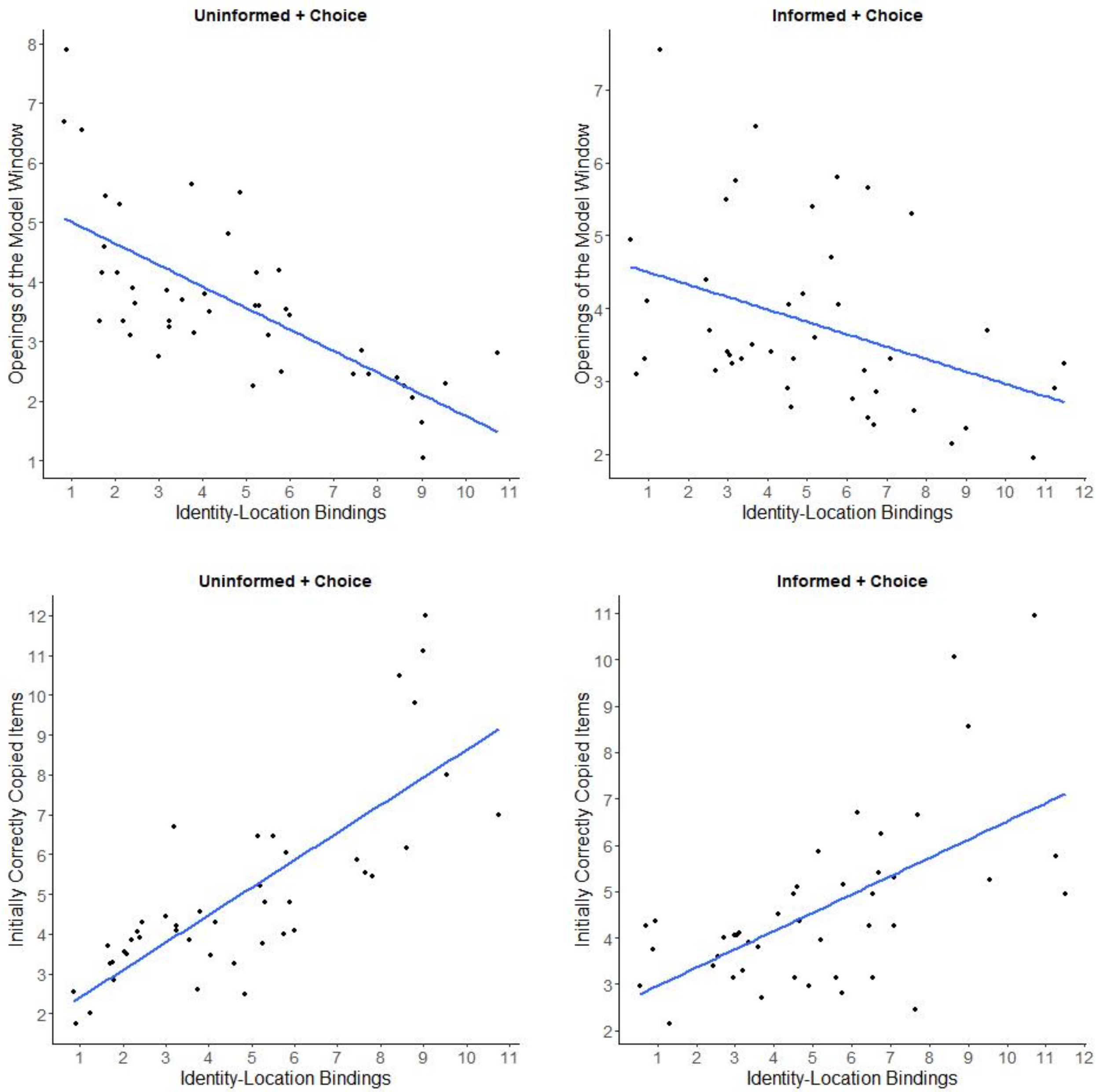


Figure 3.2. Scatter Plots of Correlational Analyses between Cognitive Offloading and Memory Performance (Identity-Location Bindings) for Experiment 3 (see also Table 16 in Chapter 4).

Plots for Experiment 1

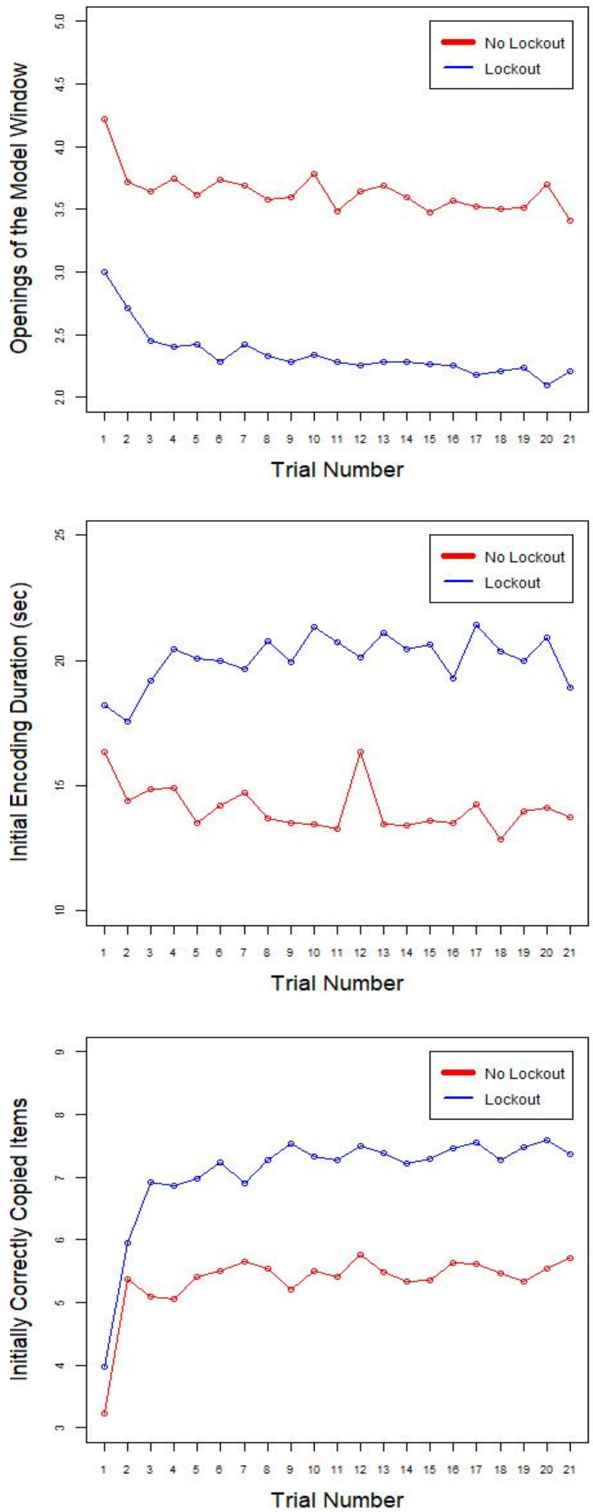


Figure 4. Plots of Offloading Behavior across Trials in Pattern Copy Task in Experiment 1. The first trial (Trial Number 1) was the practice trial, followed by twenty test trials (Trial Number 2-21).

Plots for Experiment 2

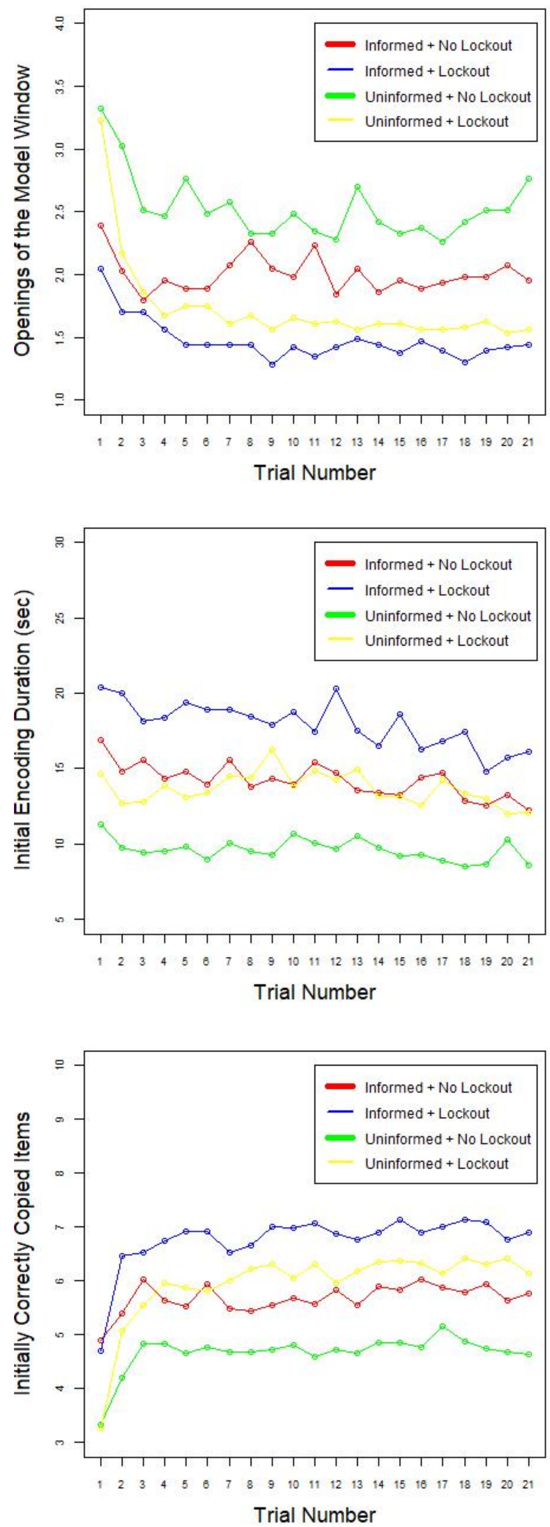
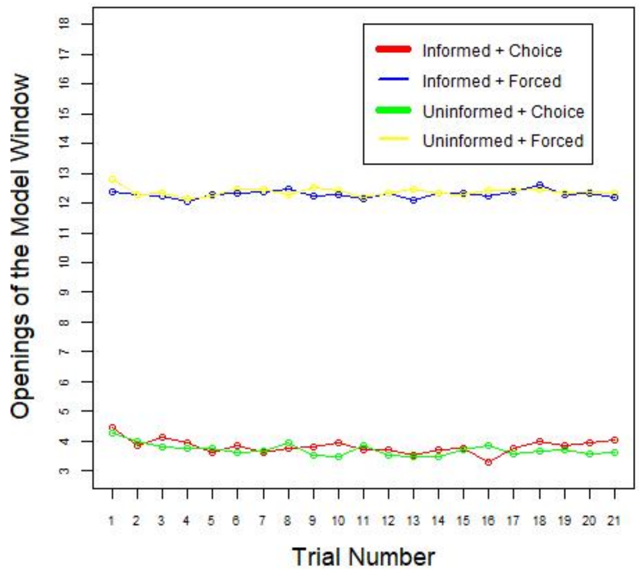


Figure 5. Plots of Offloading Behavior across Trials in Pattern Copy Task in Experiment 2. The first trial (Trial Number 1) was the practice trial, followed by twenty test trials (Trial Number 2-21).

Plots for Experiment 3



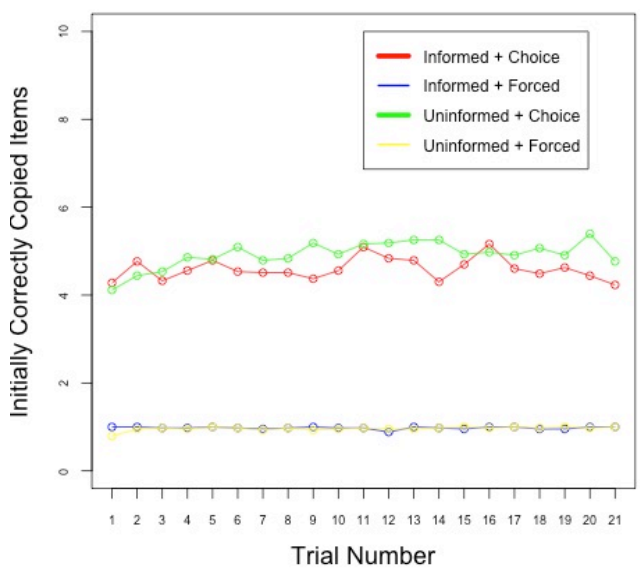


Figure 6. Plots of Offloading Behavior across Trials in Pattern Copy Task in Experiment 3. The first trial (Trial Number 1) was the practice trial, followed by twenty test trials (Trial Number 2-21).

Correlations for Experiment 1

Table 1. *Pearson-Correlations Between Working Memory Capacity and Cognitive Offloading, Immediate Task Performance as Well as Memory Performance in Experiment 1*

	Cognitive Offloading	
	Openings of the Model Window	
	No Lockout	Lockout
Working Memory Capacity		
Visual Patterns Test	-.35***	-.22*
Corsi Blocks Task	-.29**	-.06
	Initial Encoding Duration (sec)	
	No Lockout	Lockout
Visual Patterns Test	.34**	-.04
Corsi Blocks Task	.28**	-.02
	Initially Correctly Copied Items	
	No Lockout	Lockout
Visual Patterns Test	.39***	-.11
Corsi Blocks Task	.38***	.004
	Immediate Task Performance	
	Trial Duration (sec)	
	No Lockout	Lockout
Visual Patterns Test	.07	-.32**
Corsi Blocks Task	-.09	-.23*
	Errors	
	No Lockout	Lockout
Visual Patterns Test	-.26*	-.26*
Corsi Blocks Task	-.09	-.04
	Memory Performance	
	Identity	
	No Lockout	Lockout
Visual Patterns Test	.28**	.09
Corsi Blocks Task	.26*	-.13
	Identity-Location Bindings	
	No Lockout	Lockout
Visual Patterns Test	.38***	.17
Corsi Blocks Task	.33**	-.08
	Identity-Location Bindings (corrected)	
	No Lockout	Lockout
Visual Patterns Test	.37***	.17
Corsi Blocks Task	.33**	-.08

Note: * $p < .05$, ** $p < .01$, *** $p < .001$

Correlations for Experiment 2

Table 2. *Pearson-Correlations Between Working Memory Capacity and Cognitive Offloading, Immediate Task Performance as Well as Memory Performance in Experiment 2*

	Cognitive Offloading			
	Openings of the Model Window			
	No Lockout		Lockout	
	Uninformed	Informed	Uninformed	Informed
Working Memory Capacity				
Visual Patterns Test	-.51***	-.32*	-.38*	-.33*
Corsi Blocks Task	-.21	-.07	-.11	-.19
	Initial Encoding Duration (sec)			
	No Lockout		Lockout	
	Uninformed	Informed	Uninformed	Informed
Visual Patterns Test	.25	.10	.24	-.08
Corsi Blocks Task	-.15	-.04	.15	.005
	Initially Correctly Copied Items			
	No Lockout		Lockout	
	Uninformed	Informed	Uninformed	Informed
Visual Patterns Test	.38*	.34*	.24	-.21
Corsi Blocks Task	.01	.14	.03	.16
	Immediate Task Performance			
	Trial Duration (sec)			
	No Lockout		Lockout	
	Uninformed	Informed	Uninformed	Informed
Visual Patterns Test	-.27	-.10	-.01	-.41**
Corsi Blocks Task	-.41*	-.19	-.08	-.18
	Memory Performance			
	Identity			
	No Lockout		Lockout	
	Uninformed	Informed	Uninformed	Informed
Visual Patterns Test	.37*	.23	.15	.04
Corsi Blocks Task	-.04	-.09	.21	.02
	Identity-Location Bindings			
	No Lockout		Lockout	
	Uninformed	Informed	Uninformed	Informed
Visual Patterns Test	.32*	.27	.08	.19
Corsi Blocks Task	.01	-.06	.09	.17

Note: * $p < .05$, ** $p < .01$, *** $p < .001$

Correlations for Experiment 3

Table 3. *Pearson-Correlations Between Working Memory Capacity and Cognitive Offloading, Immediate Task Performance as Well as Memory Performance in Experiment 3*

	Cognitive Offloading			
	Openings of the Model Window		No analyses with forced condition due to no variance in offloading data	
	Choice			
	Uninformed	Informed		
Working Memory Capacity				
Visual Patterns Test	-.22	-.39**		
Corsi Blocks Task	-.12	.06		
	Initially Correctly Copied Items			
	Choice			
	Uninformed	Informed		
Visual Patterns Test	-.03	.04		
Corsi Blocks Task	-.002	-.23		
	Immediate Task Performance			
	Trial Duration (sec)			
	Choice		Forced	
	Uninformed	Informed	Uninformed	Informed
Visual Patterns Test	-.50***	-.33*	-.19	-.11
Corsi Blocks Task	-.31*	-.24	-.36*	.06
	Memory Performance			
	Identity			
	Choice		Forced	
	Uninformed	Informed	Uninformed	Informed
Visual Patterns Test	-.003	.18	.07	.22
Corsi Blocks Task	.03	.04	.14	.24
	Identity-Location Bindings			
	Choice		Forced	
	Uninformed	Informed	Uninformed	Informed
Visual Patterns Test	.01	.01	.16	.17
Corsi Blocks Task	.10	.09	.13	.28

Note: * $p < .05$, ** $p < .01$, *** $p < .001$