When and why we choose to offload information: Understanding the ongoing trade-off between internal memory storage and external sampling

Writing Assignment

Lisa Elbertse
Neuroscience and Cognition
Student number: 6410243

16-06-2023

Abstract

During everyday life, individuals constantly make decisions to store information internally in their working memory or externally using cognitive offloading. This trade-off can be seen as a cost-benefit analysis, in which individuals constantly need to weigh the benefit of cognitive offloading against the cost of storing the information internally. One intriguing topic in cognitive offloading research is why and when people tend to offload information externally rather than actively holding an internal representation. This review aims to investigate this trade-off by integrating recent research into cognitive offloading behaviour, and thereby specifying factors that can affect this behaviour. We conclude that increasing the cost of externalizing memory resulted in less offloading behaviour. Furthermore, other factors such as increasing memory load, lower memory capacity, lower memory confidence, older age, and memory deficits, made the benefit outweigh the cost attached to cognitive offloading, causing individuals to make more use of cognitive offloading. Results also suggest that these individual and group differences are at least partly driven by metacognitive processes and perceived cognitive effort. These factors could contribute to practical implications for designing tools and interventions that influence individuals' offloading behaviour and support information processing and storage in daily life.

Keywords: Cognitive offloading, Working memory, Individual differences, Metacognition, Cognitive effort, Group differences

Plain language summary

If your answer to one of the following questions is ‘yes’, you, among many other people, make use of the so-called principle ‘cognitive offloading’. Do you program appointments into your calendar? Or do you put your keys next to the door, so you don’t forget to bring them with you? These are all examples of cognitive offloading which can be described as the process of using external tools such as your calendar to help you remember information. If you don’t use it, all information needs to be remembered by your brain solely. Your memory has a limited capacity so the use of cognitive offloading in daily life can be very useful.

In daily life, people are constantly making the decision to store information internally in their working memory or externally with the use of cognitive offloading. This decision can be seen as a cost-benefit analysis because individuals constantly need to weigh the benefit of using cognitive offloading against the cost of storing the information internally in their memory. In scientific research, the phenomenon of cognitive offloading is mostly investigated with the use of two tasks. The first task is the copying task, during this task individuals need to recreate a model. The individuals can make use of cognitive offloading by looking at the model more often to store new information in their memory. The other task is the intention offloading task, during which individuals need to put ten circles in a numerical sequence. However, some circles need to be dragged to other places on the screen. The individuals can make use of cognitive offloading during the task by setting reminders for the location of these ‘special’ circles.

Several factors could influence the decision, that we constantly make during daily life, on where to store information. These factors could be task specific, such as increasing the cost attached to cognitive offloading during a task or increasing the amount of information that needs to be remembered (memory load). Other factors that could influence the decision differ between individuals, such as the capacity of their internal memory storage or the confidence that they have about their own memory performances. One other factor that could potentially have an effect is the cognitive effort that is attached to the act of remembering information. Individuals tend to avoid cognitive effort because of the limited capacity of their memory storage. Group differences such as age or patient groups could also have an effect on the decision to offload information or not. This review looked at studies that investigated the effects of these factors and thereby made several conclusions. First, increasing the cost of cognitive offloading made individuals offload less information. Furthermore, increasing the memory load, lower internal memory capacity, lower confidence in their memory, older age and memory deficits made individuals offload more information to external tools. These factors could therefore contribute to practical implications for designing tools and environments that influence individuals’ behaviour and support information processing and storage in daily life, such as note-taking apps, reminder systems, virtual assistants, and cognitive training software. These tools can be of particular importance for specific groups such as older adults and patients with memory deficits to help them stay independent.

1. Introduction

Have you ever programmed an appointment at the dentist into your calendar, so you did not need to keep remembering the exact date and time constantly? Or did you put something next to your door, so you did not forget to bring it with you? If your answer to one of these questions is 'yes', you are among many other people that use cognitive offloading to externalize memory. In all these everyday life examples individuals make use of their memory to perform a planned action or recall a planned intention at a future point in time (Henry et al., 2004a). Individuals can rely on their external world to support their memory, by using cognitive offloading. Cognitive offloading is a memorization strategy which is defined as 'the use of physical action to alter the information processing requirements of a task so as to reduce cognitive demand' (Risko & Gilbert, 2016). In daily life, people are constantly making the decision to store information internally in working memory or to offload information externally. This trade-off can be seen as a cost-benefit analysis, individuals constantly need to weigh the benefit of cognitive offloading against the cost of storing the information internally. This review is looking for a way to approach these decisions in everyday life, where people dynamically interact with their environment. This can be broader than just looking at exactly how much information we remember, but also how we deal with this information when it is, or is not, available and whether we make the choice to store it internally.

One example of the broader concept of cognitive offloading is intention offloading, that is defined as 'the process of creating a cue in the external world to trigger a delayed intention' (Gilbert et al., 2023). These cues in the external world can consist of external tools, e.g., calendars, diaries, strategically placed objects, sticky notes and other individuals, but also more digital technologies such as notifications on smartphones or other wearable devices are on the rise. Cognitive offloading as a strategy to externalize memory can be investigated using different paradigms. One can think of the copying task where the task is to copy a model, during which individuals can choose to memorize just one piece of information at a time, rather than memorizing it all at once (Sahakian et al., 2023; Somai et al., 2020). Or the intention offloading task in which individuals can use reminders to remember intentions (Gilbert, 2015a). The process of sampling a certain number of items into working memory during the copying task can be seen as the internalization of these items. Frequent sampling during this task can therefore be seen as a cognitive offloading strategy: copying items one at a time (thus frequent sampling) puts less cognitive demand on working memory. This reflects the real world where objects usually remain accessible and can be reinspected by reorientating to the object in the external world (Van der Stigchel, 2020).

Studies have tried to investigate the ongoing tradeoff between offloading information and internally storing it with the use of these paradigms. Ballard et al. (1995) made it more costly to access information in the external world and observed that individuals chose to offload less information. Somai et al. (2020) and Sahakian et al. (2023) also showed that increasing the cost of sampling in a copying task resulted in less sampling and an increased dwell time on the model. These results show that when the cost of cognitive offloading increases, individuals tend to offload less information and store more information in their working memory. These studies contribute to the idea that the trade-off between storing information internally in working memory and offloading information externally, is based on an adaptive mechanism, governed by cost-efficiency, and that several factors could influence this trade-off.

The aim of this literature study is to look at these adaptive decisions that individuals constantly need to make during everyday life, thereby investigating why and when people tend to offload information externally rather than actively holding an internal representation. Studying this trade-off, and the factors affecting it is relevant for several reasons. A better understanding of how individuals make adaptive decisions about information storage gives insight into how individuals effectively manage the cognitive demands of everyday life. If we find that people are weighing specific factors in the decision to offload or memorize information, we can suggest that these factors can have practical implications for designing tools and interventions that support information processing and storage in daily life. When it is clear why and when individuals are more likely to offload information externally, it could inform the design process of cognitive aids in daily life. Examples of these cognitive aids are note-taking apps, reminder systems, virtual assistants, and cognitive training software. These cognitive aids can help individuals remember important information and make cognitive resources available for other tasks. This can be particularly important for specific groups, such as older adults or patients with memory deficits. It may help to improve the behavioural independence of these groups, which could have become worse due to e.g., age, illness, or trauma. These interventions could play an important role in health-related intentions such as medication adherence or rehabilitation (Steinkamp et al., 2019).

2. The Trade-Off between internal and external memory storage

When people interact with information from their environment, they have the option to either actively hold an internal representation in their working memory or use their environment to externalize the information and sample it later. If the information is needed to perform an action, the relevant information is selected, and an active internal representation is held in working memory to either manipulate it, or use it in the original form later. If the information is not immediately needed to perform an action, an individual can choose to use cognitive offloading to externalize the information to another location. This trade-off is a dynamic balance that consists of two options.

2.1 Internal memory storage

The first option of the trade-off on where to store information is to store it internally in working memory or prospective memory. Working memory is the short-term storage that manipulates incoming sensory information (Baddeley, 2003). The classical view has been that the capacity limits of working memory should be interpreted as discrete slots, such as Miller's magical number seven (Miller, 1956) or Cowan's four (Cowan, 2001). Information either gets into one of the slots and is thereby remembered correctly, or the information does not get into one of the slots and is therefore not remembered at all (Luck & Vogel, 1997). Recent psychophysical studies on working memory have led to reasons to review this slot model of working memory. In fact, these studies showed that the precision of the recall of items declined continuously as the number of items that needed to be remembered increased (Bays et al., 2009). Furthermore, follow-up studies showed that increasing the salience or goal relevance of an item, caused it to be stored in working memory with more precision, thereby causing poorer memory for other items in working memory (Gorgoraptis et al., 2011). These findings don't support the idea behind the slot model, that every item in working memory is either stored with high accuracy and precision or not stored at all (Luck & Vogel, 1997). More recent studies have resulted in models that consider working memory to be a limited resource that is distributed flexibly between all items in a scene (Ma et al., 2014). In contrast with the slot model, these resource models do not include a maximum capacity for the number of items that can be stored in working memory. It rather focuses on the quality and precision of the items that are stored. The idea behind these resource models is that the representation of the information is noisy, i.e., the representations are stored with random, unpredictable fluctuations. This noise increases with the number of items present in working memory. More items cause more noise, due to the limited resources in working memory that are available. Therefore, the more available resource that is allocated to an item, the less noise there is on its representation, causing a more accurate and precise representation (Ma et al., 2014). Even though the concept of resource models has considerable explanatory power, more behavioural research is needed to establish a sound theoretical framework for these working memory models. The memory system that is used for information that is related to delayed intentions is called prospective memory (Walter & Meier, 2014). Failures of this memory system cause individuals to forget delayed intentions in everyday life, e.g., forgetting that they needed to buy eggs at the store on their way home. Individuals tend to forget delayed intentions because these intentions are often not effectively triggered by cues in our environment, therefore the action of a delayed intention needs to be remembered and self-initiated by the individual.

So, although it is feasible that incoming information is stored in resource models or prospective memory, this still requires an individual to actively hold this information in their memory. This option of the trade-off is associated with a high internal cognitive effort and makes other items in memory noisier. Individuals can therefore not decide to simply store all information internally, as their memory capacity is not unlimited and storage becomes very inaccurate. Therefore there must be an effective and accurate other side to the trade-off, which depends on the external world.

2.2 External environment

The other side of the trade-off on where to store information is to use the external world and sample the information later. This so-called cognitive offloading of information into the external world plays an undeniable role in our everyday cognitive lives (Schönpflug, 1986). Cognitive offloading is used as a strategy to suppress the need for an internal representation of information in working memory. With the use of cognitive offloading individuals alter their environment to store information or intended behaviour that needs to be remembered for a later moment in time (Nestojko et al., 2013). Individuals can easily sample information into their memory with the use of eye movements. This decision to resample information at a later time point can be seen as a form of cognitive offloading, where individuals decide to perform a physical action to reduce their internal cognitive effort (Sahakian et al., 2023). External tools can be used to offload information temporarily and sample it back into memory at a later time point when the information is needed to perform an action. Examples of these external tools are post-it notes or task-relevant objects, but also smartphones or other wearable devices are used to provide location- or time-based reminders (McDonald et al., 2011). This form of cognitive offloading has been referred to as intention offloading: 'the process of creating a cue in the external world to trigger a delayed intention' (Gilbert et al., 2023). This type of cognitive offloading requires more 'action' from the individual itself, the individual actively needs to use a reminder to trigger the delayed intention at a later time point. Clark & Chalmers (1998) already came up with the extended mind thesis, which states that a person's mind and associated cognitive processing extend into the external world. This concept is in line with the concept of incorporating external aids into cognitive processing. In other words, by cognitive offloading, the individual creates a transactive memory system in which information is assigned between internal and external memory resources (Wegner & Ward, 2013). To conclude, cognitive offloading with the use of sampling can overcome the well-established capacity limits of working memory, and thereby help the individual remember information and intentions at a later time point (Morrison & Richmond, 2020).

3. How to measure the trade-off

In daily life people are constantly making the decision to store information internally or externally. This dynamic trade-off can be investigated in a more experimental setting than in daily life, with the use of different paradigms. This chapter will outline different paradigms that are used most often in cognitive offloading research, chapter 4 will outline the results and conclusions of studies that used these paradigms.

3.1 Copying task

As described above, the act of making an eye movement can be seen as using the external world to store information externally. The trade-off is in this case between the costs of storing the visual features of an object in visual working memory (VWM) and the benefit associated with the execution of an eye movement (Van der Stigchel, 2020). This trade-off for visual information is investigated in an experimental setting where individuals can choose to make an eye movement to sample one or more items into VWM, instead of loading all items directly into VWM. One used paradigm to measure this form of cognitive offloading is the 'copying task'. In the copying task, the participant needs to recreate a model of an arrangement of items at another location, during the task the model always remains accessible. Participants need to pick up items from a set of 'Resources' and recreate a replica of the model in their own 'Workspace' (Fig 1; Sahakian et al., (2023)). The main outcome measure in studies that use this paradigm is how often and how long participants reinspect the Model and thereby sample items into their VWM. Studies that used this copying task found that participants inspected the model relatively often. Participants first inspected the Model to identify which item they needed to pick up and subsequently looked at the Model again to determine where to place it in their Workspace. This suggests that participants rely little on their VWM capacity when it is not necessary to use it (Ballard et al., 1995; Somai et al., 2020).

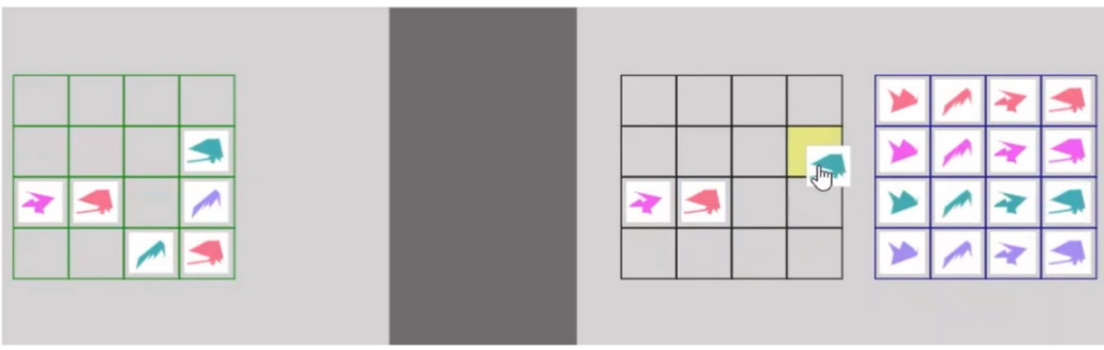

Fig. 1 Adopted from Sahakian et al. (2023). An overview of the copying task. Left is a model of an arrangement of items. On the right are the Workspace and the Resources that can be dragged into the correct position in the Workspace.

Over the years, researchers came up with variations on the standard copying task, with the aim to influence the trade-off between sampling and VWM utilization by adding costs to the action of making a saccade to sample information. The idea behind this is, that if the trade-off is dynamic; adding a cost to the trade-off will influence the decision that the individuals make. If the cost of making a saccade becomes too high and does not outweigh the benefit, individuals will make fewer saccades and sample more information in their VWM. Ballard et al. (1995) came up with a variation on the task in which they increased the cost of making a saccade to the model. The cost of making a saccade was increased by placing the location of the Model and Workspace farther away from each other, causing the participants to make a larger head movement to sample the items in the Model. Droll & Hayhoe (2007) manipulated another aspect of the task, they increased the cognitive cost by increasing the number of visual features that needed to be remembered or changing the task demands, causing a higher working memory load. The idea behind this manipulation was to see if participants would switch to a strategy that relied more on using external information by making more saccades toward the Model.

Somai et al. (2020) influenced the trade-off by adding time costs to the action of making a saccade, by adding a delay to the availability of the Model (Fig. 2; Somai et al., (2020)). The Model was removed from the screen when the participant looked at their Workspace, when the participant made a saccade back to the Model, the presentation of the Model was delayed in time. By adding this delay, the time cost of using external information was increased. This variation on the copying task had three different time costs, the Model reappeared after 250, 1500, or 3000ms.

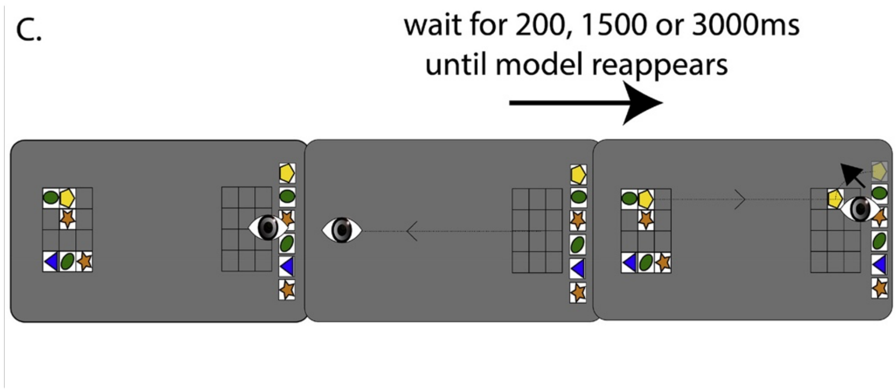

Fig. 2 Adopted from Somai et al. (2020). Overview of the task. Left is the start of the experiment where the model grid was visible. If a saccade was made across the middle of the screen the Model was occluded. The delay in the presence of the Model was either 200ms, 1500ms, or 3000ms after which the Model reappeared.

Sahakian et al. (2023) designed a copying task similar to the study of Somai et al. (2020) but with one addition. Participants were interrupted while creating a replica of the Model in the Workspace. Importantly, the interruptions were unpredictable and timed when participants tried to make a saccade toward the Model (so just before they resampled the items in the Model). During these interruptions, a probe question was shown on the screen (Fig. 3; Sahakian et al., (2023)) to investigate the content of the participant's VWM and their memory confidence.

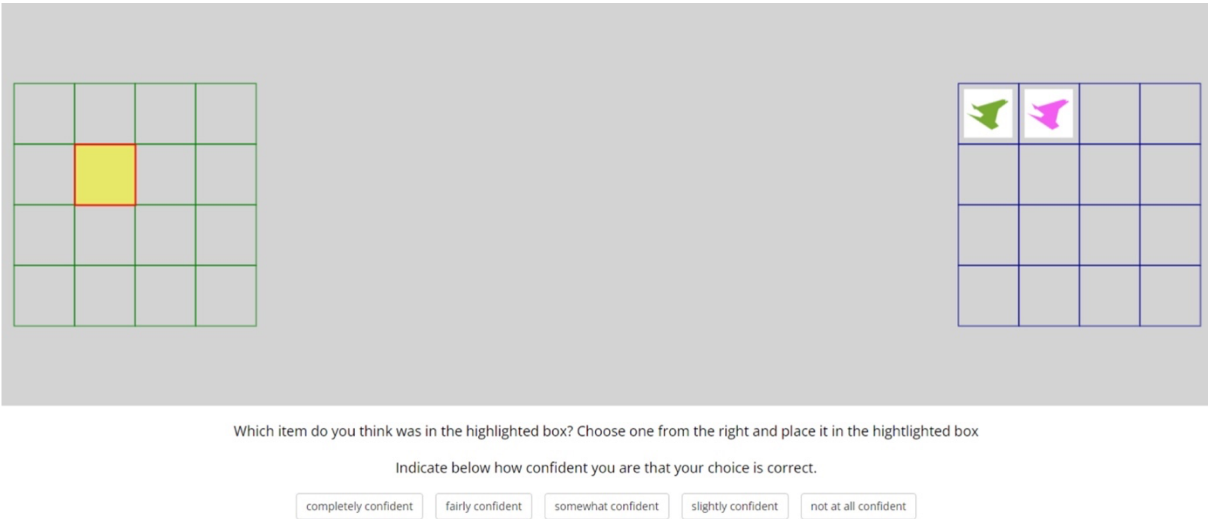

Fig. 3 Adopted from Sahakian et al. (2023). The screen that is shown during the interruptions. One cell in the model was highlighted, and the participant was asked to indicate which of the two items shown in the Workspace belonged to that cell in the Model. The participants also needed to indicate how confident they were that their choice was correct, with the use of a question at the bottom of the screen.

3.2 Intention offloading task

A paradigm in which specifically intention offloading is measured is the intention offloading task (Fig. 4; Gilbert (2015a)). The participants need to drag ten circles in numerical sequence to the bottom of a box on the screen. At the beginning of each trial, instructions are shown on the screen. E.g., 'Please drag the circle with the number 6 to the left instead'. These types of instructions cause delayed intentions when the participant needs to drag the numbers to the assigned place. The trade-off is simulated in this paradigm as follows: participants can remember the nonstandard instructions internally in their working memory, or they can offload the information with the use of external reminders. For example, dragging the circle with the number 6 to the left side directly after the instructions are shown. By doing so the participant will be reminded of the instructions when they get to the number 6 in the sequence, and therefore don't need to actively hold the information in their working memory constantly. This procedure can be compared to the example in the introduction of placing an item next to the door so that you don't forget it when you leave the house. Before starting the task, participants are instructed that they have a free choice about whether they use external reminders as a strategy or remember the intentions in their internal memory. The outcome measure for the intention offloading task is the rate of setting a reminder (i.e., the proportion of circles for which participants use intention offloading as a memory strategy).

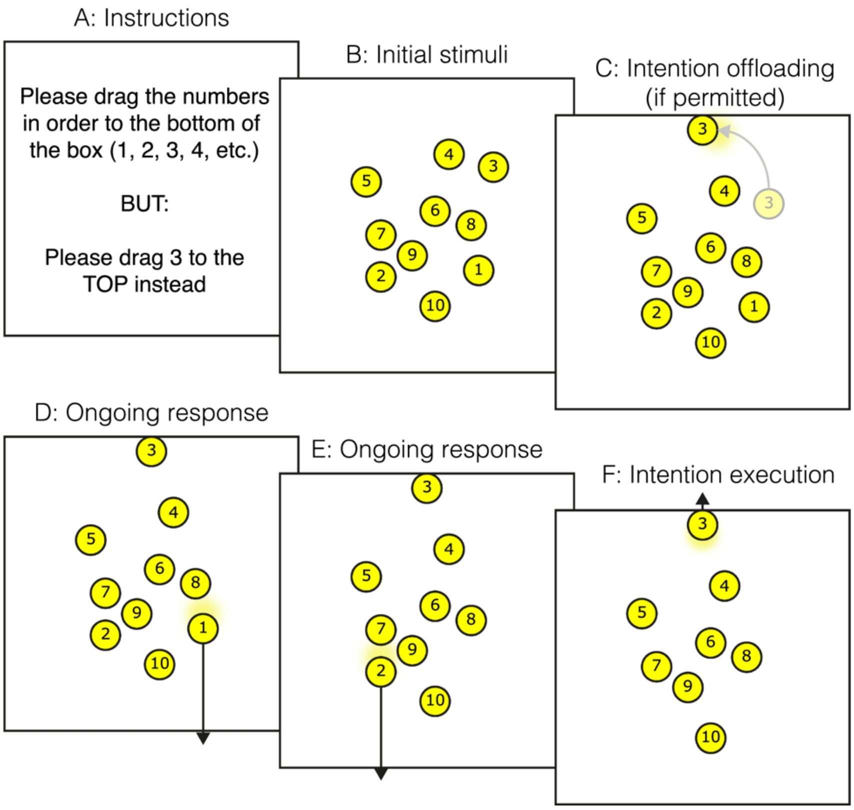

Fig. 4 Adopted from Gilbert (2015a). Overview of the intention offloading task. The circles need to be dragged down in numerical sequence to the bottom of the box.

In daily life people constantly need to make decisions about whether the benefit of setting a reminder (increased chance of remembering) outweighs the cost of a reminder (time and effort of setting the reminder). The intention offloading paradigm described above does not consider how accurate the decisions of participants are. It only measures how often participants set reminders. Therefore, Gilbert et al. (2019) made some adjustments to the task so that the new paradigm considers whether participants make accurate decisions or not (Fig. 5; Gilbert et al. (2019)). The task itself is the same as described above, participants are offered a choice between (1) using their internal memory, or (2) using external memory with the use of reminders. If they choose option (1) they earn maximum points, if they choose option (2) they earn fewer points which vary each trial. For example, during one trial a participant can earn 10 points per correct item when using their internal memory only, and 5 points per correct item using reminders. Suppose that the participant can achieve 55% accuracy using their internal memory and achieve 100% accuracy by using reminders. The optimal choice for this trial would be to use internal memory (5.5 points per item) compared to using reminders (5 points per item). To calculate the optimal strategy for each individual participant, the participants are forced to use either internal memory or reminders in some trials. This is then used to calculate the accuracy for both conditions which is used to calculate their most accurate strategy on the choice trials. This most accurate strategy is then compared to their actual choice on the choice trials and used to measure whether the participant uses the optimal number of reminders, more reminders than would be optimal, or fewer reminders than would be optimal.

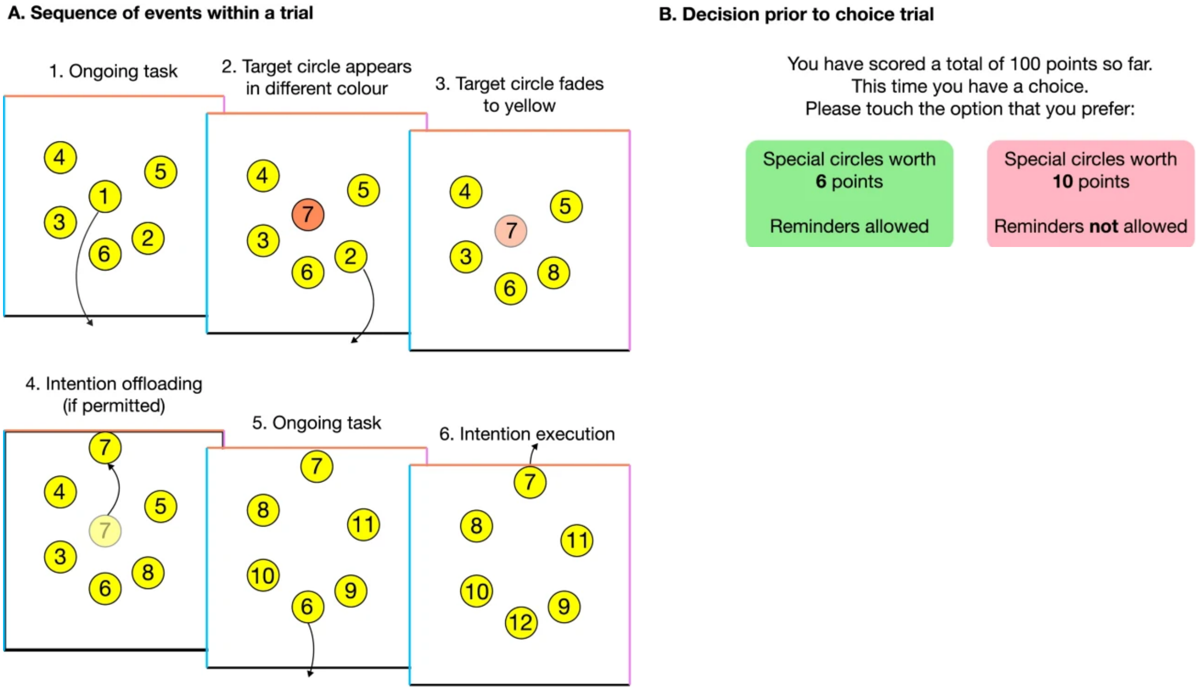

Fig. 5 Adopted from Gilbert et al. (2019). Overview of the intention offloading task with the optimal reminder's manipulation. During some trials circles appear in a color that matches one side of the box, this is an instruction to drag that specific circle to that side of the box when it is reached in the sequence.

Initial research on both tasks specifically showed that individuals tend to rely more on externalizing memory than would be most accurate for the task, and therefore choose a more minimalistic memory strategy with less internal memory storage (Ballard et al., 1995; Gilbert et al., 2019). Even though they are capable to remember all information they tend to still use cognitive offloading to externalize their memory. Meyerhoff et al. (2021) performed a study in which they compared the two tasks described above and examined the relations between individual differences in the copying task and the intention offloading task. They showed that individual differences in cognitive offloading behaviour were not significantly correlated between a copying task and the intention offloading task, despite sufficiently reliable measures in both tasks. This insignificant correlation shows that it is unlikely that the bias towards cognitive offloading can be explained directly in terms of a single common factor driving offloading behaviour across different offloading tasks. If this was the case, and a single common factor such as memory capacity or metacognition would explain offloading behaviour across different tasks, individual differences would have been significantly correlated with each other.

4. Factors that influence the trade-off

The most intriguing question in research on cognitive offloading is: 'Why and when do people tend to offload information externally rather than memorize it internally.' This trade-off can be seen as an effort-based cost-benefit analysis, and several considerations may enter this dynamic weighting. First, it involves a cost to make an eye movement or to set up a reminder. Individuals need to consider the significance of the information to be remembered in relation to the goal of a task. For some tasks, it may be useful to use cognitive offloading to complete the task successfully. Like in the intention offloading task, it is useful to set some reminders for the delayed intentions to get high accuracy. In other situations, using cognitive offloading can be useful but not crucial for completing the task. For example, one may not write down every statement one's conversational partner makes during a conversation. It may be useful to remember some statements, but it is not crucial for the conversation to go smoothly. Second, the cost-benefit analysis involves a benefit, namely the increased chance of remembering something. Individuals constantly need to decide whether the benefit of using cognitive offloading outweighs the cost coupled with it. There are factors at play that have an influence on this cost-benefit analysis. These factors could be different for a specific task, i.e., costs related to the task or memory load during the task. Other individual factors could also have an effect on the trade-off, such as working memory capacity or memory confidence. Differences in these factors and thereby differences in task performance and strategies could possibly be explained by the influence of metacognition and cognitive effort. Lastly, these factors could differ between groups such as younger and older adults. Here, we will discuss factors that have been hypothesized to influence dynamic memory usage (e.g. memorizing vs. offloading) at personal differences and group levels that might yield individual strategies.

4.1 Task specific factors

4.1.1 Increase costs

First, we look at the influence of changing the costs of externalizing information on the trade-off. Ballard et al. (1995) were the first to investigate this effect with the use of the copying task (see Fig. 1). They concluded that executing a saccade had a lower cost attached to it than using VWM to store visual information, during the copying task. Furthermore, they concluded that increasing the cost of accessing external information, by increasing the distance between the Model and the Workspace, resulted in less offloading. Draschkow et al. (2021) replicated this study and also concluded that participants relied more on their VWM content when the costs of externalizing memory increased. Somai et al. (2020) and Sahakian et al. (2023) also investigated the effect of increasing the cost attached to externalizing memory but used a delay in the presentation of the Model as a way of increasing the cost (see Fig. 2). Both studies also concluded that increasing the cost of externalizing memory resulted in less resampling and therefore less cognitive offloading. All described studies on increasing the cost of externalizing memory, therefore, conclude that as the cost of externalizing memory increases, be it by increasing distance, locomotion effort, or a delay in presentation, observers show less offloading behaviour and increase their reliance on internal memory.

4.1.2 Memory load

Opposite to the manipulations performed by the studies described above, another way of investigating the trade-off is by increasing the demand for working memory. By increasing this demand, observers might offset the cost by frequently using external memory to acquire the necessary information. Droll & Hayhoe (2007) performed such a manipulation in their study. They increased the working memory load in a copying task to see if observers would switch to a strategy that includes more cognitive offloading, and therefore rely more on their external memory. They increased the memory load by randomizing the features of the items that were relevant to remember. Because observers could not anticipate which feature would be relevant for sorting until later, they either had to decide to store all features in their VWM or choose to resample the features later, by making saccades to the model again. This resampling was seen as storing information externally. The authors concluded that observers were much more likely to offload information into external memory when the memory load was increased. Similarly, Gilbert (2015b) used the intention offloading task and manipulated memory load by varying the number of intentions that needed to be remembered. Observers indeed adapted the number of reminders they used to the increased memory load. The increase in memory demands of the task made observers more likely to engage in offloading behaviour. Redshaw et al. (2018) replicated the study of Gilbert (2015) in a group of children and found the same results on cognitive offloading behaviour. All described studies on increasing the memory load in a cognitive offloading task therefore conclude that as the memory load in a task increases, observers tend to use more cognitive offloading to externalize their memory.

To conclude, increasing the cost of externalizing memory makes individuals less likely to engage in offloading behaviour. On the contrary, increasing the memory load during a task makes individuals more likely to engage in offloading behaviour.

4.2 Individual differences

4.2.1 Working memory capacity

As described above, studies concluded that memory load has an influence on offloading behaviour. This suggests that working memory capacity also plays a role in offloading behaviour. Multiple studies have examined the relationship between cognitive offloading behaviour and working memory capacity. All these studies hypothesized a relation between these two because cognitive offloading could potentially compensate for a lower internal capacity of working memory. Gilbert (2015) investigated this hypothesis with the use of the intention offloading task. Risko & Dunn (2015) also investigated the relation but with the use of a memory span test (in which observers were able to use cognitive offloading by note taking). In both studies working memory capacity was inversely related to the frequency of cognitive offloading. In other words, the observers that had a higher memory capacity were less likely to offload information externally, when given the opportunity. In addition, Morrison & Richmond (2020) added two span tasks for independent estimates of working memory capacity. The authors were able to replicate the experimental findings of Risko & Dunn (2015). On the contrary, they were not able to observe a correlation between working memory capacity on the independent task, and cognitive offloading behaviour. These conflicting results led Meyerhoff et al. (2021) to use the Corsi blocks tapping task (adapted from Milner 1971) for measuring independent working memory capacity. The authors concluded that cognitive offloading behaviour is correlated with working memory capacity. Observers with lower working memory capacity tend to compensate for this with the use of more cognitive offloading. Ball et al. (2022) also investigated this correlation and indeed found that observers with lower working memory capacity chose to make more use of cognitive offloading, suggesting that they were less able to use internal memory storage. Therefore, almost all described studies on the relationship between working memory capacity and cognitive offloading behaviour conclude that observers with lower working memory capacity tend to use more cognitive offloading as the memory load in a task increased. Suggesting that observers tend to use more cognitive offloading to compensate for a lower internal capacity of their working memory.

4.2.2 Metacognition

Besides all other factors that Gilbert (2015a) investigated in his studies on cognitive offloading, he also investigated the effect of memory confidence on cognitive offloading behaviour. As described above, individuals tend to offload more information externally when their working memory capacity is lower. This raises the question of whether individuals also tend to offload more information when their confidence about their memory capacity is lower, to compensate for their lower subjective memory ratings. One could imagine that individuals sample more often to ‘check’ their memory once they have lower confidence in their memory. The subjective memory ratings were gathered after the practice trials. Participants were asked to provide a prediction of what percentage of items they thought they would drag to the instructed locations in the intention offloading task. Gilbert (2015a) indeed found that lower subjective memory ratings predicted intention offloading behaviour. Individuals with lower subjective memory ratings tend to use more reminders as a compensatory strategy. Three other studies used the same paradigm and also found that lower memory confidence in individuals was associated with increased cognitive offloading, indicating the use of a compensatory strategy (Ball et al., 2022; Boldt & Gilbert, 2019; Kirk et al., 2021).

The studies described above show that individuals tend to offload more information when their memory performance on a task is poorer or task demands are higher (i.e., with a lower (subjective) working memory capacity or with a higher memory load). These results could potentially be explained by the influence of metacognition on cognitive offloading behaviour. Metacognition refers to a range of processes involved in reflecting on one's mental states, including the ability to estimate confidence in one's performance on a task (Fleming et al., 2012; Yeung & Summerfield, 2012). Individuals tend to offload more information when their memory processes are insufficient, this suggests that individuals rely on their metacognitive evaluations of their own memory performance in the decision to offload information or not (Gilbert et al., 2023).

Evidence for this hypothesis was found by Gilbert (2015a). In the study, observers performed the intention offloading task in two separate Phases. In Phase 1 observers could rely on their internal memory only, in Phase 2 the observers got the option to use cognitive offloading by setting reminders. At each Phase, participants were asked to give metacognitive performance evaluations by moving a slider ranging from 0% to 100%. The results showed that the probability of using offloading in Phase 2 was predicted by objective unaided accuracy in Phase 1 (how much they actually *needed* offloading). In addition, the probability of using offloading in Phase 2 was also predicted by individuals' metacognitive evaluations in Phase 1 (how much they *thought* they needed offloading). Boldt & Gilbert (2019) designed a follow-up study in which one group was explicitly instructed on how to use cognitive offloading by setting reminders. A second group was not instructed with any instructions but was allowed to use reminders if they spontaneously invented the strategy themselves. Individuals in the spontaneous group indeed showed offloading behaviour, but they used it less often than the group that was explicitly instructed. Individuals with lower metacognitive evaluations were more likely to show offloading behaviour, regardless of their objective memory ability. This suggests that offloading behaviour is guided by metacognition.

Another study by Gilbert et al. (2019) also provided evidence for the role of metacognition on cognitive offloading. In this study, individuals underwent metacognitive interventions to influence their metacognitive beliefs during the task. These interventions consisted of manipulations of the difficulty of the practice trials, or in the form of feedback that the individuals received. This feedback consisted out of positive or negative sentences about their level of performance, such as 'You responded correctly to most of the circles!' or 'Room for improvement, you got some of the circles wrong'. First, the study showed that the metacognitive interventions affected subjective confidence, individuals had significantly more confidence after they received positive feedback. There was no effect on individuals' objective accuracy on the task. Second, the study showed that the metacognitive interventions also affected offloading behaviour: when individuals had more confidence, they made less use of cognitive offloading by setting fewer reminders. Further analysis showed that shifts in the frequency of offloading behaviour were mediated by shifts in confidence. The authors came up to the conclusion that metacognitive interventions can affect offloading behaviour without affecting objective memory performance, therefore concluding a metacognitive influence on cognitive offloading. Based on these findings Engeler & Gilbert (2020) investigated whether metacognitive training is an effective intervention to improve metacognitive judgement accuracy and reduce bias in cognitive offloading behaviour. This metacognitive training consisted of individuals making performance predictions and receiving feedback on these predictions afterwards. Results showed that metacognitive training increased judgement accuracy. Individuals in the control group were significantly less confident about their working memory capacity, whereas the experimental group did not show any metacognitive bias. However, both groups were significantly biased towards more frequent offloading. The authors concluded that reducing metacognitive bias was not enough to eliminate the bias towards frequent offloading, this suggests that the bias towards frequent offloading behaviour cannot be fully explained by metacognition.

4.2.3 Cognitive Effort

In the study of Gilbert et al. (2019) described above, one group got only easy practice trials and positive feedback. This group of participants was significantly over-confident about their subjective memory capacity, suggesting that this group would show less cognitive offloading behaviour. However, this group still made use of more cognitive offloading than would have led to optimal memory performance. Therefore, the study showed that a positive cognitive offloading bias can be observed in both over- and under-confident participants, these results suggest that there must be other factors involved. One such factor that may influence the decision to offload information externally or store it internally is a preference to avoid cognitive effort (Shenhav et al., 2017). Theories about cognitive effort in cognitively demanding tasks argue that the feeling of cognitive effort arises from the involvement of domain general processes that can only be involved in a limited number of tasks at the same time (Kurzban et al., 2013). Using cognitive effort on one task therefore prevents its use on other tasks. An aversion against cognitive effort can therefore be seen as a drive to reduce the use of these domain general processes. This concept is often called the 'law of less work', when given a choice between similarly rewarding options, individuals typically learn to avoid the option that requires more work or effort (Hull, 1943).

Internal memory has well-known limits to its capacity for information that can be actively stored (Bays & Husain, 2008). The cost of maintaining one item may prevent another item to be maintained in working memory, causing a feeling of high cognitive effort. External tools and reminders such as mobile devices rather have an unlimited capacity, and the use of them as external memory therefore causes a feeling of low cognitive effort. This concept may explain why individuals tend to decide to offload information rather than store it internally in working memory. Sachdeva & Gilbert (2020) investigated whether this effort-avoidance can explain a cognitive offloading bias that is associated with storing less information internally. They investigated this by adding performance-based financial rewards to the intention offloading task. The authors hypothesized that if it is the case that cognitive offloading behaviour is not influenced by perceived cognitive effort, it should not matter whether performance is encouraged with a financial reward. Participants would in that case be selecting their optimal strategies based on their metacognitive beliefs only. By contrast, if cognitive effort avoidance does contribute to the strategy decision, the use of reminders should be reduced by financial incentives. This idea was derived from the fact that individuals are more likely to exert cognitive effort when they have a financial incentive to do this (Aarts et al., 2010; Padmala & Pessoa, 2011). Sachdeva & Gilbert (2020) indeed found that the bias towards avoiding perceived cognitive effort using external reminders was significantly reduced, but not eliminated, when the participants received a financial reward for their performance. These results suggest that cognitive effort, but also external incentives, indeed contribute to individuals' cognitive offloading behaviour.

4.3 Ageing

Studies have found that in laboratory settings, younger participants usually outperform older participants on memory tasks, suggesting an age-related decline in memory performance (Henry et al., 2004b; Kliegel et al., 2008). Given the evidence that metacognitive processes guide cognitive offloading behaviour (Engeler & Gilbert, 2020; Sachdeva & Gilbert, 2020). Together with the evidence that brain regions related to metacognition, e.g., regions in the prefrontal and parietal cortex, are predisposed to ageing-related atrophy (Tisserand et al., 2004) and that this could cause metacognitive deficits. It is relevant to look at the influence of ageing on these metacognitive processes and the effect on cognitive offloading behaviour. As mentioned above, low memory confidence can lead to increased cognitive offloading indicating the use of a compensatory strategy. Studies suggest that particularly older adults may have low memory confidence (Touron & Hertzog, 2004), suggesting that this would therefore lead to increased cognitive offloading. Scarampi & Gilbert (2021) investigated this hypothesis by administering an intention offloading task to two groups. One group consisted of a group of younger adults (18 to 30 years), while the other group consisted of older adults (65 to 84 years). They used a version of the intention offloading task in which they manipulated the memory load, and whether participants were allowed to use cognitive offloading by using reminders. The results did not support the hypothesis that older participants would show an increased preference for cognitive offloading. The older group did perform significantly worse than the younger group in both conditions in which cognitive offloading was permitted or not. However, when both groups were given the option to set reminders, older adults did not show a significant increase in preference for cognitive offloading. Thereby concluding that older adults don't compensate fully for working memory decline associated with ageing.

After these somewhat surprising results, Tsai et al. (2022) performed a follow-up study in which they used the version of the intention offloading task in which optimal use of reminders was measured (See Fig. 5; Gilbert et al., 2019). Older adults again performed significantly worse than the younger group on memory performance, but this time they were also significantly more likely to use cognitive offloading. However, when including the level of performance, older adults were - relative to their performance - less likely to use cognitive offloading compared to younger adults. Their level of performance was lower than the level of performance of the younger adults, therefore the older adults still set numerically more reminders but used relatively less cognitive offloading. Younger adults were on the contrary underconfident about their working memory capacity and tended to be biased to use cognitive offloading even though the optimal strategy was to use internal memory only. Older adults did not show a significant bias to use cognitive offloading. Burnett & Richmond (2023) performed a study in which two groups of young and older adults were asked to do a retrospective audiovisual working memory task. Cognitive offloading was only permitted in one of the two conditions. Both age groups' performance was improved in the condition where they were permitted to use cognitive offloading. Furthermore, the authors did not find any difference in the choice to use cognitive offloading at high memory loads between the two groups. Furthermore, cognitive offloading benefitted performance for both groups similarly. The authors thereby concluded that older adults make effective use of cognitive offloading as a strategy to compensate for their decline in memory performance related to ageing. Pizzonia & Suhr, (2019) reviewed the literature on internal and external memory strategy use in older adults. They concluded that overall increased age was associated with a decrease in internal memory storage and an increase in external memory use.

To conclude, older adults seem to use more cognitive offloading as a memory strategy than younger adults. This difference seems to be explained by an increased *need* for reminders in older adults, rather than an increased *preference* for using reminders to externalize memory. Older adults do not seem to have the metacognition to understand that they need reminders to perform better. A possible explanation for these findings is a different level of memory confidence that is observed between younger and older adults (Gilbert et al., 2023).

4.4 Patient groups

All studies discussed so far have been conducted in a healthy population. In fact, it is very valuable to also look at patient groups with memory impairments since they can possibly struggle with storing the right information. One study by Cherkaoui & Gilbert (2017) investigated whether individuals with autism spectrum conditions (ASC) compensate for their impaired memory performance when they have the option to set external reminders. The results however showed that individuals with ASC performed worse than neurotypical and that this was even true when they had the option to use cognitive offloading. Another study by Böing et al. (2023) investigated how memory deficits in individuals with Korsakoff amnesia impact the trade-off between storing internally or sampling externally. The study compared the sampling behaviour of individuals with Korsakoff amnesia and healthy controls on a copying task (see Fig. 2). The authors concluded that patients sampled more often and longer. When the cost of sampling became higher due to a waiting time, controls showed reduced sampling and memorized more internally. Patients also showed reduced sampling when the cost became higher, this result suggests that despite their memory deficits patients still attempted memorisation. In addition, patients sampled disproportionately more than controls, but their accuracy on the task dropped. This suggests that patients with memory deficits do not compensate for increased sampling costs by memorising more, indicating that they rely more on their external world with the use of cognitive offloading than healthy controls.

These two studies are a first step in identifying how memory deficits in patient groups impact the trade-off between internal information storage and external sampling with cognitive offloading. However, more research on cognitive offloading behaviour in different patient groups and types of memory deficits is needed to come up with effective interventions for memory deficits in daily life.

5. Discussion

During everyday life, individuals constantly make decisions to store information internally in their working memory or externally using cognitive offloading. We reviewed literature on this adaptive decision that individuals constantly make during everyday life, thereby investigating why and when people tend to offload information externally and sample it later, rather than actively holding an internal representation. Cognitive offloading is the decision of an individual to use a physical action such as an eye movement to alter the information processing requirements of a task so as to reduce cognitive demand (Risko & Gilbert, 2016). The trade-off that can be seen as a cost-benefit analysis, could potentially be influenced by various factors.

All included studies concluded that as the cost of externalizing memory increased, be it by increasing distance, locomotion effort or a delay in presentation, observers show less offloading behaviour and increase their reliance on internal memory. Furthermore, studies on the effect of memory load in a cognitive offloading task concluded that as the memory load in a task increases, observers tend to use more cognitive offloading to externalize memory. Almost all studies on the relationship between working memory capacity and cognitive offloading behaviour concluded that observers tend to use more cognitive offloading to compensate for a lower internal capacity of their working memory. Morrison & Richmond (2020) were the only that surprisingly did not find this result, they came up with two explanations for their unexpected results. First, all students that were included in the study reported fluency in English, however, a considerable number of students were non-native English speakers. This in combination with the use of single letters in the task may have influenced overall accuracy. The second potential reason for the surprising results is that during the task the items were only presented in the auditory modality. It is therefore possible that participants experienced difficulties with phonologically similar letter perception, and therefore chose the wrong letter to report. However, Risko & Dunn (2015) used the same paradigm and population in their study and did find that observers tend to use more cognitive offloading to compensate for a lower internal capacity of their working memory. Therefore, it is hard to say if auditory-only stimuli were the cause of the surprising results. The studies on memory confidence were more in accordance with each other. All concluding that lower memory confidence in individuals was associated with increased cognitive offloading, indicating the use of a compensatory strategy. Another conclusion that can be drawn from the studies reviewed above, is that individual differences in cognitive offloading behaviour are at least partly driven by metacognitive processes and evaluations of cognitive effort. Metacognitive interventions can cause individuals to have more confidence in their working memory capacity, and therefore use cognitive offloading more optimally (Gilbert et al., 2019). All studies on the effect of ageing on cognitive offloading behaviour concluded that older adults make more use of cognitive offloading, although they don't show a preference for using reminders. This suggests that older adults are not aware of their memory decline and are confident about their own memory performances (Pizzonia & Suhr, 2019). To date, only a few studies looked at how memory deficits in patient groups can impact the trade-off on the dynamic interplay between internal storage and external sampling. One study on memory deficits in individuals with ASC concluded that patients performed worse than neurotypical and that this was even true when they had the option to use cognitive offloading. One study found the same results for individuals with Korsakoff amnesia but also found that patients sampled disproportionately more than controls, but their accuracy on the task still dropped. This suggests that patients with memory deficits due to Korsakoff amnesia do not compensate for increased sampling costs by memorising more, and thereby rely more on their external memory than healthy controls. To summarize, various factors at individual and group levels have been investigated and all influence the dynamic memory usage (e.g. memorizing vs. offloading) that yield individual memory strategies in daily life. We can see that all these factors affect how we deal with information from the outside world. In everyday life, all these factors and more play a role at the same time and thus affect each other. However, these factors are almost always studied in isolation in experimental settings. Therefore, future research should not study these factors in isolation but rather look at how the factors affect each other and thereby the trade-off.

Several limitations need to be considered when reviewing the current literature on cognitive offloading. First, all studies integrated in this study look at cognitive offloading behaviour measured in experimental tasks like the copy task and intention offloading task. One question that arises from this concerns the relationship between these experimental environments and people's everyday life and cognitive offloading behaviour in the real world. Individuals' decisions in everyday life are more complex and influenced by more factors than experimental settings could potentially capture. Furthermore, all studies typically measure individuals' use of explicitly instructed offloading strategies, this contrasts with everyday life where offloading strategies are generated mostly spontaneously. Therefore, future studies should include more naturalistic approaches such as observations of naturalistic behaviour in the real world or for example diary studies. With the growing impact of technology on everyday life, future studies could investigate how the use of technology such as smartphones and virtual assistants influences cognitive offloading behaviour and whether individuals' cognitive offloading behaviour differs between these digital tools and for example the use of paper. Smits et al. (2022) looked at the effectiveness of a smartwatch as an external memory aid compared to verbal in-person reminders in Korsakoff patients. The study showed that the accuracy on memory tasks did not significantly differ between the smartwatch reminders and verbal in-person reminders. One study by Scullin et al. (2022) investigated the use of smartphone technology to improve memory functioning in older adults and concluded that older adults with cognitive disorders can learn technology-based memory strategies and doing so benefits memory functioning and independence. This independence is important for the current ageing population, where individuals are advancing in age. These smartphone technologies could potentially be effective for everyday functional impairments in dementia, where effective pharmacological treatments are currently still absent.

Second, the current study integrated and compared the results from various studies that used different variations on the copying task and intention offloading task. One potential objection against these methods and interpretations might be that the two cognitive offloading tasks vary in several features and therefore results should not be compared. The underlying processes of the tasks may differ in the way that the copying task involves replicating information from a model to a target area, while the intention offloading task involves the conscious decision to offload information to an external aid. Furthermore, the two tasks also differ in several surface features, e.g., the presence of external cues and the number of objects. Therefore, future research should take these differences into account when studies using different cognitive offloading tasks are compared.

Third, another possible limitation in the studies on the influence of metacognition in the trade-off is that the measure that was used for metacognition could potentially be inaccurate. Participants got the metacognitive interventions only at the beginning of the task. It is possible that participants became less confident as the experimental trials progressed because the interventions were too long ago to still influence offloading behaviour. However, if this was indeed the case, this was not captured because the scale used to measure metacognition was only shown to the participants after the practice trials, and not during the experimental trials. This underconfidence with practice (UWP) effect (Koriat et al., 2002), meaning the more the participant practice, the more underconfident they become in their cognitive abilities, can be an explanation for the biases towards cognitive offloading. The participants might have been overconfident at the beginning of the task and therefore offloaded less, but slowly became less confident as they got more practice and started to become biased towards offloading.

To conclude, this review summarized the current state of knowledge on cognitive offloading literature, with a focus on individual and group differences that affect cognitive offloading behaviour. The adaptive decision that individuals constantly make during everyday life to store information internally or externally can be seen as an effort-based cost-benefit analysis. Individuals constantly need to decide whether the benefit of using cognitive offloading outweighs the cost coupled to the offloading. Increasing the cost of externalizing memory outweighed the benefit attached to it, resulting in less offloading behaviour. Furthermore, other factors such as increasing memory load, lower memory capacity, lower memory confidence, older age and memory deficits made the benefit outweigh the cost attached to cognitive offloading, causing individuals to make more use of cognitive offloading. So a complex interplay of factors seems to underlie final offload behaviour in individuals. These factors could therefore contribute to practical implications for designing tools and environments that influence individuals' offloading behaviour and support information processing and storage in daily life, such as note-taking apps, reminder systems, virtual assistants, and cognitive training software. These technical tools can be of particular importance for specific groups such as older adults and patients with memory deficits to help them remember important information and stay independent of others. Nonetheless, a noticeable difference exists between the experimental studies and the practical implications of cognitive offloading behaviour in the real world. Closing this gap could potentially contribute to the adaptive use of cognitive offloading and promote individuals' independence in daily life.

References

Aarts, E., Roelofs, A., Franke, B., Rijpkema, M., Fernández, G., Helmich, R. C., & Cools, R. (2010). Striatal Dopamine Mediates the Interface between Motivational and Cognitive Control in Humans: Evidence from Genetic Imaging. *Neuropsychopharmacology 2010 35:9*, *35*(9), 1943–1951. https://doi.org/10.1038/npp.2010.68

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience 2003 4:10*, *4*(10), 829–839. https://doi.org/10.1038/NRN1201

Ball, H., Peper, P., Alakbarova, D., Brewer, G., & Gilbert, S. J. (2022). Individual differences in working memory capacity predict benefits to memory from intention offloading. *Memory*, *30*(2), 77–91. https://doi.org/10.1080/09658211.2021.1991380/SUPPL_FILE/PMEM_A_1991380_SM5033.DOCX

Ballard, D. H., Hayhoe, M. M., & Pelz, J. B. (1995). Memory Representations in Natural Tasks. *Journal of Cognitive Neuroscience*, *7*(1), 66–80. http://direct.mit.edu/jocn/article-pdf/7/1/66/1932431/jocn.1995.7.1.66.pdf

Bays, P. M., Catalao, R. F. G., & Husain, M. (2009). The precision of visual working memory is set by allocation of a shared resource. *Journal of Vision*, *9*(10), 7–7. https://doi.org/10.1167/9.10.7

Bays, P. M., & Husain, M. (2008). Dynamic shifts of limited working memory resources in human vision. *Science*, *321*(5890), 851–854. https://doi.org/10.1126/SCIENCE.1158023/SUPPL_FILE/BAYS.SOM.PDF

Böing, S., Ten Brink, A. F., Hoogerbrugge, A. J., Oudman, E., Postma, A., Nijboer, T. C. W., Van Der Stigchel, S., & Nl, A. F. T. B. J. H. (2023). Clinical Medicine Eye Movements as Proxy for Visual Working Memory Usage: Increased Reliance on the External World in Korsakoff Syndrome. *J. Clin. Med. 2023*, *12*, 3630. https://doi.org/10.3390/jcm12113630

Boldt, A., & Gilbert, S. J. (2019). Confidence guides spontaneous cognitive offloading. *Cognitive Research: Principles and Implications*, *4*(1), 1–16. https://doi.org/10.1186/S41235-019-0195-Y/FIGURES/5

Burnett, L. K., & Richmond, L. L. (2023). Just write it down: Similarity in the benefit from cognitive offloading in young and older adults. *Memory and Cognition*, *1*, 1–13. https://doi.org/10.3758/S13421-023-01413-7/FIGURES/2

Cherkaoui, M., & Gilbert, S. J. (2017). Strategic use of reminders in an 'intention offloading' task: Do individuals with autism spectrum conditions compensate for memory difficulties? *Neuropsychologia*, *97*, 140–151. https://doi.org/10.1016/J.NEUROPSYCHOLOGIA.2017.02.008

Clark, A., & Chalmers, D. (1998). The Extended Mind. *Analysis*, *58*(1), 7–19. https://doi.org/10.1093/ANALYS/58.1.7

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*(1), 87–114. https://doi.org/10.1017/S0140525X01003922

Draschkow, D., Kallmayer, M., & Nobre, A. C. (2021). When Natural Behavior Engages Working Memory. *Current Biology*, *31*(4), 869-874.e5. https://doi.org/10.1016/J.CUB.2020.11.013

Droll, J. A., & Hayhoe, M. M. (2007). Trade-offs Between Gaze and Working Memory Use. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(6), 1352–1365. https://doi.org/10.1037/0096-1523.33.6.1352

Engeler, N. C., & Gilbert, S. J. (2020). The effect of metacognitive training on confidence and strategic reminder setting. *PLOS ONE*, *15*(10), e0240858. https://doi.org/10.1371/JOURNAL.PONE.0240858

Fleming, S. M., Dolan, R. J., & Frith, C. D. (2012). Metacognition: computation, biology and function. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*(1594), 1280–1286. https://doi.org/10.1098/RSTB.2012.0021

Gilbert, S. J. (2015a). Strategic offloading of delayed intentions into the external environment. *Quarterly Journal of Experimental Psychology*, *68*(5), 971–992. https://doi.org/10.1080/17470218.2014.972963/ASSET/IMAGES/LARGE/10.1080_17470218.2014.972963-FIG4.JPEG

Gilbert, S. J. (2015b). *Strategic use of reminders: Influence of both domain-general and task-specific metacognitive confidence, independent of objective memory ability*. https://doi.org/10.1016/j.concog.2015.01.006

Gilbert, S. J., Bird, A., Carpenter, J. M., Fleming, S. M., Sachdeva, C., & Tsai, P. C. (2019). Optimal Use of Reminders: Metacognition, Effort, and Cognitive Offloading. *Journal of Experimental Psychology: General*. https://doi.org/10.1037/XGE0000652

Gilbert, S. J., Boldt, A., Sachdeva, C., Scarampi, C., & Tsai, P. C. (2023). Outsourcing Memory to External Tools: A Review of 'Intention Offloading.' *Psychonomic Bulletin and Review*, *30*(1), 60–76. https://doi.org/10.3758/S13423-022-02139-4

Gorgoraptis, N., Catalao, R. F. G., Bays, P. M., & Husain, M. (2011). Dynamic Updating of Working Memory Resources for Visual Objects. *Journal of Neuroscience*, *31*(23), 8502–8511. https://doi.org/10.1523/JNEUROSCI.0208-11.2011

Henry, J. D., MacLeod, M. S., Phillips, L. H., & Crawford, J. R. (2004a). A Meta-Analytic Review of Prospective Memory and Aging. *Psychology and Aging*, *19*(1), 27–39. https://doi.org/10.1037/0882-7974.19.1.27

Henry, J. D., MacLeod, M. S., Phillips, L. H., & Crawford, J. R. (2004b). A meta-analytic review of prospective memory and aging. *Psychology and Aging*, *19*(1), 27–39. https://doi.org/10.1037/0882-7974.19.1.27

Hull, C. (1943). *Principles of behavior: an introduction to behavior theory.* https://psycnet.apa.org/record/1944-00022-000

Kirk, P. A., Robinson, O. J., & Gilbert, S. J. (2021). Trait anxiety does not correlate with metacognitive confidence or reminder usage in a delayed intentions task. *Quarterly Journal of Experimental Psychology*, *74*(4), 634–644. https://doi.org/10.1177/1747021820970156/ASSET/IMAGES/LARGE/10.1177_1747021820970156-FIG5.JPEG

Kliegel, M., Jäger, T., & Phillips, L. H. (2008). Adult Age Differences in Event-Based Prospective Memory: A Meta-Analysis on the Role of Focal Versus Nonfocal Cues. *Psychology and Aging*, *23*(1), 203–208. https://doi.org/10.1037/0882-7974.23.1.203

Koriat, A., Sheffer, L., & Ma'ayan, H. (2002). Comparing objective and subjective learning curves: Judgments of learning exhibit increased underconfidence with practice. *Journal of Experimental Psychology: General*, *131*(2), 147–162. https://doi.org/10.1037/0096-3445.131.2.147

Kurzban, R., Duckworth, A., Kable, J. W., & Myers, J. (2013). An opportunity cost model of subjective effort and task performance. *Behavioral and Brain Sciences*, *36*(6), 661–679. https://doi.org/10.1017/S0140525X12003196

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature 1997 390:6657*, *390*(6657), 279–281. https://doi.org/10.1038/36846

Ma, W. J., Husain, M., & Bays, P. M. (2014). Changing concepts of working memory. *Nature Neuroscience*, *17*(3), 347–356. https://doi.org/10.1038/NN.3655

McDonald, A., Haslam, C., Yates, P., Gurr, B., Leeder, G., & Sayers, A. (2011). Google Calendar: A new memory aid to compensate for prospective memory deficits following acquired brain injury. *Http://Dx.Doi.Org.Proxy.Library.Uu.Nl/10.1080/09602011.2011.598405*, *21*(6), 784–807. https://doi.org/10.1080/09602011.2011.598405

Meyerhoff, H. S., Grinschgl, S., Papenmeier, F., & Gilbert, S. J. (2021). Individual differences in cognitive offloading: a comparison of intention offloading, pattern copy, and short-term memory capacity. *Cognitive Research: Principles and Implications*, *6*(1), 1–18. https://doi.org/10.1186/S41235-021-00298-X/FIGURES/7

Miller, G. A. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological Review*, *63*(2), 81–97. https://doi.org/10.1037/H0043158

Milner, B. (1971). *Interhemispheric differences in the localization of psychological processes in man.* https://psycnet.apa.org/record/1972-32010-001

Morrison, A. B., & Richmond, L. L. (2020). Offloading items from memory: individual differences in cognitive offloading in a short-term memory task. *Cognitive Research: Principles and Implications*, *5*(1), 1–13. https://doi.org/10.1186/S41235-019-0201-4/FIGURES/4

Nestojko, J. F., Finley, J. R., & Roediger, H. L. (2013). Extending Cognition to External Agents. *Https://Doi-Org.Proxy.Library.Uu.Nl/10.1080/1047840X.2013.844056*, *24*(4), 321–325. https://doi.org/10.1080/1047840X.2013.844056

Padmala, S., & Pessoa, L. (2011). Reward Reduces Conflict by Enhancing Attentional Control and Biasing Visual Cortical Processing. *Journal of Cognitive Neuroscience*, *23*(11), 3419–3432. https://doi.org/10.1162/JOCN_A_00011

Pizzonia, K. L., & Suhr, J. A. (2019). Systematic Review of Correlates of Internal and External Memory Strategy Use in Older Adults. *Systematic Reviews Journal of Applied Gerontology*, *2022*(5), 1491–1499. https://doi.org/10.1177/07334648211065427

Redshaw, J., Vandersee, J., Bulley, A., & Gilbert, S. J. (2018). Development of Children's Use of External Reminders for Hard-to-Remember Intentions. *Child Development*, *89*(6), 2099–2108. https://doi.org/10.1111/CDEV.13040

Risko, E. F., & Dunn, T. L. (2015). Storing information in-the-world: Metacognition and cognitive offloading in a short-term memory task. *Consciousness and Cognition*, *36*, 61–74. https://doi.org/10.1016/J.CONCOG.2015.05.014

Risko, E. F., & Gilbert, S. J. (2016). Cognitive Offloading. *Trends in Cognitive Sciences*, *20*(9), 676–688. https://doi.org/10.1016/J.TICS.2016.07.002

Sachdeva, C., & Gilbert, S. J. (2020). Excessive use of reminders: Metacognition and effort-minimisation in cognitive offloading. *Consciousness and Cognition*, *85*, 103024. https://doi.org/10.1016/J.CONCOG.2020.103024

Sahakian, A., Gayet, S., Paffen, C. L. E., & Van der Stigchel, S. (2023). Mountains of memory in a sea of uncertainty: Sampling the external world despite useful information in visual working memory. *Cognition*, *234*. https://doi.org/10.1016/J.COGNITION.2023.105381

Scarampi, C., & Gilbert, S. J. (2021). Age differences in strategic reminder setting and the compensatory role of metacognition. *Psychology and Aging*, *36*(2), 172–185. https://doi.org/10.1037/PAG0000590

Schönpflug, W. (1986). The trade-off between internal and external information storage. *Journal of Memory and Language*, *25*(6), 657–675. https://doi.org/10.1016/0749-596X(86)90042-2

Scullin, M. K., Jones, W. E., Phenis, R., Beevers, S., Rosen, S., Dinh, K., Kiselica, A., Keefe, F. J., & Benge, J. F. (2022). Using smartphone technology to improve prospective memory functioning: A randomized controlled trial. *Journal of the American Geriatrics Society*, *70*(2), 459–469. https://doi.org/10.1111/JGS.17551

Shenhav, A., Musslick, S., Lieder, F., Kool, W., Griffiths, T. L., Cohen, J. D., & Botvinick, M. M. (2017). Toward a Rational and Mechanistic Account of Mental Effort. *Https://Doi.Org/10.1146/Annurev-Neuro-072116-031526*, *40*, 99–124. https://doi.org/10.1146/ANNUREV-NEURO-072116-031526

Smits, S., Oudman, E., Altgassen, M., & Postma, A. (2022). Smartwatch reminders are as effective as verbal reminders in patients with Korsakoff's syndrome: three case studies. *Https://Doi.Org/10.1080/13554794.2021.2024237*, *28*(1), 48–62. https://doi.org/10.1080/13554794.2021.2024237

Somai, R. S., Schut, M. J., & Van der Stigchel, S. (2020). Evidence for the world as an external memory: A trade-off between internal and external visual memory storage. *Cortex*, *122*, 108–114. https://doi.org/10.1016/J.CORTEX.2018.12.017

Steinkamp, J. M., Goldblatt, N., Borodovsky, J. T., LaVertu, A., Kronish, I. M., Marsch, L. A., & Schuman-Olivier, Z. (2019). Technological Interventions for Medication Adherence in Adult Mental Health and Substance Use Disorders: A Systematic Review. *JMIR Ment Health 2019;6(3):E12493 Https://Mental.Jmir.Org/2019/3/E12493*, *6*(3), e12493. https://doi.org/10.2196/12493

Tisserand, D. J., Van Boxtel, M. P. J., Pruessner, J. C., Hofman, P., Evans, A. C., & Jolles, J. (2004). A Voxel-based Morphometric Study to Determine Individual Differences in Gray Matter Density Associated with Age and Cognitive Change Over Time. *Cerebral Cortex*, *14*(9), 966–973. https://doi.org/10.1093/CERCOR/BHH057

Touron, D. R., & Hertzog, C. (2004). Distinguishing age differences in knowledge, strategy use, and confidence during strategic skill acquisition. *Psychology and Aging*, *19*(3), 452–466. https://doi.org/10.1037/0882-7974.19.3.452

Tsai, P., Scarampi, C., Kliegel, M., & Gilbert, S. (2022). *Optimal cognitive offloading: Increased reminder usage but reduced pro-reminder bias in older adults*. https://psyarxiv.com/2cghy/download?format=pdf
Van der Stigchel, S. (2020). An embodied account of visual working memory. *Visual Cognition*, *28*(5–8), 414–419. https://doi.org/10.1080/13506285.2020.1742827
Walter, S., & Meier, B. (2014). How important is importance for prospective memory? A review. *Frontiers in Psychology*, *5*(JUN), 657. https://doi.org/10.3389/FPSYG.2014.00657/ABSTRACT
Wegner, D. M., & Ward, A. F. (2013). How google is changing your brain. *Scientific American*, *309*(6), 58–61. https://doi.org/10.1038/SCIENTIFICAMERICAN1213-58
Yeung, N., & Summerfield, C. (2012). Metacognition in human decision-making: confidence and error monitoring. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*(1594), 1310–1321. https://doi.org/10.1098/RSTB.2011.0416