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Optimal use of reminders: Metacognition, effort, and cognitive offloading

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Abstract

Individuals frequently choose between accomplishing goals using unaided cognitive abilities or offloading cognitive demands onto external tools and resources. For example, in order to remember an upcoming appointment one might rely on unaided memory or create a reminder by setting a smartphone alert. Setting a reminder incurs both a cost (the time/effort to set it up) and a benefit (increased likelihood of remembering). Here we investigate whether individuals weigh such costs/benefits optimally or show systematic biases. In three experiments, participants performed a memory task where they could choose between a) earning a maximum reward for each remembered item, using unaided memory, or b) earning a lesser amount per item, using external reminders to increase the number remembered. Participants were significantly biased towards using external reminders, even when they had a financial incentive to choose optimally. Individual differences in this bias were stable over time, and predicted by participants' erroneous metacognitive underconfidence in their memory abilities. Bias was eliminated, however, when participants received metacognitive advice about which strategy was likely to maximize performance. Furthermore, we found that metacognitive interventions (manipulation of feedback valence and practice-trial difficulty) yielded shifts in participants' reminder bias that were mediated by shifts in confidence. However, the bias could not be fully attributed to metacognitive error. We conclude that individuals have stable biases towards using external versus internal cognitive resources, which result at least in part from inaccurate metacognitive evaluations. Finding interventions to mitigate these biases can improve individuals' adaptive use of cognitive tools.

Keywords: prospective memory; metacognition; offloading; reminders; effort

A cardinal feature of human cognition is that we often use physical action and external resources to reduce the cognitive demands of a task, rather than relying on internal processes alone. This is known as cognitive offloading (Risko & Gilbert, 2016). For example, rather than remembering a piece of information we might use a pen and paper to write it down; rather than planning a route we might programme a GPS system to guide us; rather than remembering an upcoming appointment we might create a reminder by setting a smartphone alert. Using a reminder involves both a cost (the time and effort spent setting it up) and a benefit (the increased likelihood of remembering). In this article we address the following questions: do individuals weigh the costs and benefits of using external tools optimally, or do they show systematic biases towards the use of internal or external resources? If such biases are found, how can we explain their origins and what might we be able to do to mitigate them?

Minimal memory, soft constraints, and cognitive impartiality

The question of how we weigh decisions between using internal vs external resources has been widely discussed by cognitive scientists in recent decades. Some authors suggest that the human cognitive system has a drive to use externally represented information, and avoid internal memory representations, wherever possible. According to this 'minimal memory' view (Ballard, Hayhoe, Pook, & Rao, 1997), decisions are systematically biased towards using external resources where possible. A contrasting view is the 'soft constraints' model presented by Gray et al. (2006). According to this model, individuals do not have any systematic bias towards internal or external resources; they simply choose whichever option minimises the time taken to achieve a goal.

While the soft constraints model proposes that time is the only quantity that individuals have a drive to minimise, other theoretical frameworks suggest that cognitive effort is intrinsically costly (Shenhav et al., 2017), and therefore individuals strive to minimise the amount of effort required to perform a task (Kool, McGuire, Rosen, & Botvinick, 2010), or to balance it optimally with 'leisure' (Kool & Botvinick, 2014). This view proposes that individuals will sometimes perform a task less efficiently (e.g. more slowly), if this allows them to avoid cognitive effort. This might occur because effort is a limited resource that individuals try to conserve (Baumeister, Vohs, & Tice, 2007), although this view has encountered considerable conceptual and empirical challenges in recent years (Hagger et al., 2016; Lurquin & Miyake, 2017). An alternative account proposes that cognitively effortful tasks are those that involve relatively domain-general processes that can only be deployed for a limited number of simultaneous tasks (Kurzban, Duckworth, Kable, & Myers, 2013; see also Boureau, Sokol-Hessner, & Daw, 2015). Exercising cognitive effort on any one activity might therefore be minimized because it incurs an opportunity cost: insofar as cognitive effort is being exercised on one activity, this precludes its use on another.

One of the difficulties in evaluating how optimal individuals are at balancing internal versus external resources is that the costs of using one or the other strategy are generally not directly comparable. For example, there is no obvious scale on which the expenditure of cognitive versus physical effort can be compared (though see Chong et al., 2017; Potts, Pastel, & Rosenbaum, 2018; Schmidt, Lebreton, Cléry-Melin, Daunizeau, & Pessiglione, 2012). Progress in characterising the processes that regulate the allocation of mental effort has come from recent studies using the tools of behavioural economics (see Kool & Botvinick, 2018 for a recent review). Here we use a similar approach, investigating how individuals choose internal versus external strategies based on a single metric of task performance. We administered a memory task in which individuals repeatedly choose between two options: A) use internal memory processes alone, or B) offload memory requirements and improve performance by using external reminders. If they chose to use internal memory processes, participants always earned the maximum reward for each item they remembered. If they chose to use external reminders, they earned a lesser reward for each correct item, the precise value of which varied from trial to trial. Therefore, using reminders involved both a cost (the reduced reward) and a benefit (the increased likelihood of remembering). We investigated whether individuals weigh these costs and benefits optimally, or show systematic biases.

Sources of bias: Preference versus metacognitive error

In this paradigm, there are at least two potential causes of bias. One possibility would be that participants accurately judge the optimal decision to maximise performance, but nevertheless choose differently due to a preference towards internal vs external resources, even if this leads to suboptimal behaviour according to the reward structure of the task. For example, participants might choose to avoid an internal strategy due to its greater reliance on effortful internal memory processes. This would be consistent with the 'minimal memory' view (Ballard et al., 1997). It would also be compatible with the view that individuals avoid effort because it is intrinsically costly (Kool et al., 2010). Indeed, a study by Westbrook, Kester & Braver (2013) showed that participants will accept a financial penalty in order to perform a less cognitively effortful task. However, some authors argue that cognitive effort is not costly in all circumstances and can even be rewarding (Inzlicht, Shenhav, & Olivola, 2018). It should be noted that setting an external reminder may incur both an effort saving, seeing as it removes the need for effortful internal memory processes, and also an effort cost, due to the requirement for participants to interrupt their ongoing cognitive activities to set a reminder, before switching back to whichever task they were performing. We also note that setting an external reminder removes the need to maintain an internal representation, but individuals might continue to maintain one anyway. Therefore reminder-setting likely reduces, but does not eliminate, the use of internal memory processes.

An alternative explanation of bias would be that regardless of any systematic preference towards internal versus external strategies, individuals misjudge the efficacy of internal vs external strategies due to metacognitive error, i.e. a discrepancy between their beliefs about their abilities and their true performance level. For example, an underconfident person who believes that their internal memory abilities are poorer than they actually are might choose to use external resources not due to a preference for accomplishing the task in this way, but simply due to an incorrect belief that their performance would be poor otherwise. Consistent with this possibility, Virgo et al. (2017) have argued that individuals have a tool-related bias, such that they are systematically biased to believe that using external tools will be more efficient than internal resources, even when this is not actually true (though see Siegler & Lemaire, 1997 and Walsh & Anderson, 2009 for evidence of a bias in the opposite direction). Further evidence for a metacognitive explanation of bias comes from a study by Dunn, Lutes, & Risko (2016) which found that participants selected tasks to perform in accordance with their metacognitive evaluations of how demanding they were, rather than objective indices of task demand such as response time (see also Dunn, Gaspar, & Risko, 2019; Dunn & Risko, 2016).

It is important to note that these two possibilities are not mutually exclusive. It would be quite possible for an individual to be biased towards external strategies both due to a bias against cognitive effort, and additionally a metacognitive underconfidence in their internal abilities (i.e. lower predicted than actual accuracy). It is also possible that a preference to avoid cognitive effort is realised by an individual holding higher metacognitive confidence for external resources and/or lower confidence for internal ones. Therefore, evidence for a metacognitive influence on selection of internal versus external strategies does not rule out the possibility of a preference to avoid cognitive effort.

Intention offloading task

We used a task examining participants' memory for delayed intentions, adapted from a paradigm originally developed by Gilbert (2015a; see also Boldt & Gilbert, 2019; Cherkaoui & Gilbert, 2017; Gilbert, 2015b; Landsiedel & Gilbert, 2015; Redshaw, Vandersee, Bulley, & Gilbert, 2018). In this task participants are presented with a set of numbered circles, which they must drag in numerical order towards the bottom of the screen. They are also instructed at the beginning of each trial to drag one or more of the circles to an alternative location (e.g. drag '5' to the right). Participants can perform this task internally, by remembering the instruction until the appropriate moment (i.e. remember the instruction while they drag circles 1-4 to the bottom of the screen, then execute it when they reach number 5). Alternatively, they can 'offload' the intention by dragging the '5' circle towards the right of the screen at the beginning (akin to leaving an object by the front door so that you will remember to take it with you when you leave the house tomorrow). Subsequently, there is no need to maintain an internal representation of the intention, which is cued by the location of the target circle. Gilbert (2015a) showed that accuracy on this task significantly predicted participants' ability to fulfil an intention embedded within their everyday life over the period of one week, demonstrating significant external validity with respect to real-world prospective memory behaviour. The task is similar to standard tests of prospective memory in that it requires participants to remember to execute an intended activity after a delay, however the duration of this delay period is much shorter than standard tests. Therefore, we prefer the more theoretically neutral terminology that this task measures participants' ability to remember delayed intentions, rather than describing it as a prospective memory task (see Gilbert, 2015a for further discussion of this point).

Previous studies have given participants a free choice whether to set external reminders or simply maintain an internal representation of the intention in this task (Gilbert, 2015a, 2015b). This allows investigation of the factors that influence participants' choice of one or the other strategy. For example, participants are more likely to set external reminders when they have more items to remember or experience interruptions during the task, and older adults set more reminders than younger adults (Gilbert, 2015a). Previous studies also point to a key role of metacognitive evaluations in influencing whether individuals choose to set external reminders or use their own memory. In particular, Gilbert (2015b) found that participants with lower confidence in their memory abilities were more likely to set external reminders. This held true even after statistically controlling for actual memory ability, a finding that was replicated by Boldt and Gilbert (2019) both when the offloading strategy was explicitly instructed and when it was spontaneously generated by participants. In one experiment (Gilbert 2015b, Experiment 2a) there was no relationship between memory confidence and actual ability ($r = -.01$), yet participants with lower confidence were still more likely to set external reminders. Furthermore, individuals with lower confidence in their performance of an unrelated perceptual discrimination task were also more likely to set external reminders in the memory task, even though there was no relationship between performance in the two tasks. These findings show that individuals choose to set external reminders based on a potentially erroneous metacognitive evaluation of their memory abilities. Regardless of their actual memory abilities, participants offload memory demands into the external environment insofar as they believe that they will struggle using internal resources alone (see Risko & Dunn, 2015; Risko & Gilbert, 2016 for further evidence for a metacognitive account of cognitive offloading). This may explain why individuals offload memory demands even when their performance is already at ceiling without offloading (Risko & Dunn, 2015).

While the studies reviewed above help to identify factors that influence decisions to use internal or external resources to achieve a goal, they cannot tell us how optimal those decisions are. By considering optimality, we can address both theoretical issues and practical ones. The main theoretical issues that we can address relate to cognitive impartiality: to what extent can individuals' biases in strategy selection be attributed to a) metacognitive error; b) a preference to avoid cognitive effort; or c) a combination of the two? In practical terms, a finding of significant deviations from optimality when choosing between internal versus external resources would suggest the importance of interventions to reduce these biases. Given that technology gives us frequent opportunities to use external resources to supplement memory, navigation, arithmetic, and so on, reducing biases towards or against these resources could improve adaptive behaviour in everyday life. For example, external reminders can substantially increase the ability to remember delayed intentions in individuals with prospective memory impairment (Fish, Wilson, & Manly, 2010; Thöne-Otto & Walther, 2008; Wilson, Emslie, Quirk, & Evans, 2001). Even amongst non-impaired individuals, there are many opportunities to support memory for delayed intentions using devices such as smartphone reminders, or personal assistants such as 'Siri', 'Alexa', and 'Cortana' (Graus, Bennett, White, & Horvitz, 2016). However, such devices can only help if individuals correctly judge the benefit of setting reminders in the first place.

Two opposing predictions might be made on the basis of previous research in this field. One the one hand, laboratory studies investigating metacognitive judgements in delayed intention tasks have found that participants are generally underconfident about their internal memory abilities (Gilbert, 2015b; Meeks, Hicks, & Marsh, 2007; Rummel, Kuhlmann, & Touron, 2013; Schnitzspahn, Zeintl, Jäger, & Kliegel, 2011). This suggests that participants may show a bias towards reminders in the present study. An alternative possibility is suggested by a study by Fisher et al. (2015), who found that participants with access to an external resource (Google search engine) while completing a general knowledge task subsequently believed that they had more knowledge 'in the head' when performing an unrelated subsequent task. In other words, participants seemed to blur the distinction between metacognitive evaluation of what they know vs what the internet 'knows'. This suggests that participants who had previously had access to external resources in the form of reminders might subsequently inflate their evaluation of their internal memory abilities, leading to a bias towards an internal strategy.

Research aims

In this study we developed a task that allowed us to measure how optimal individuals are in a memory task that allows them to choose between external reminders versus unaided memory. We addressed three main questions: 1) Do individuals show systematic biases towards or away from external memory resources? 2) Are individual differences in these biases stable over time? 3) Insofar as individuals do show biases, to what extent can these be attributed to a preference towards or against cognitive effort, versus an inaccurate metacognitive evaluation of the value (i.e. likely result) of that effort?

Experiment 1

We developed a paradigm that allowed us to evaluate potential bias towards or away from external reminders using a memory task based on the intention offloading task from earlier studies (Cherkaoui & Gilbert, 2017; Gilbert, 2015a, 2015b; Landsiedel & Gilbert, 2015; Redshaw et al., 2018). We tested participants on two occasions, approximately 2-3 weeks apart. This allowed us to test whether individual differences in bias are stable over time.

Methods

Participants

41 participants took part in the study (13 male; 28 female; mean age: 25.1; range: 18-45). They were administered the present task as part of a wider study (see below) and the sample size was based on resource availability for this study. Participants were tested on two occasions 14 - 24 days apart (M=14.7, SD=2.0). All participants provided informed consent before participating and the research was approved by the UCL Research Ethics Committee.

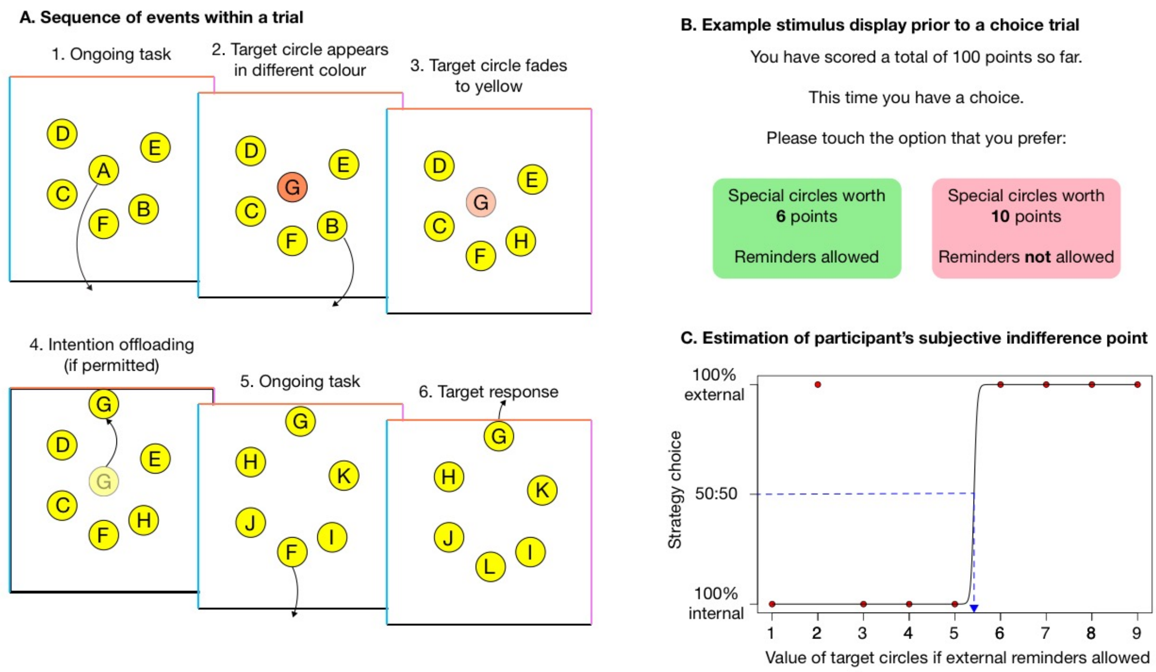

Figure 1. Schematic illustration of the optimal reminders task, and estimation of participants' indifference points.

Optimal Reminders task

See Figure 1 for a schematic illustration of the task. Participants viewed six yellow circles randomly positioned within a square, on a touchscreen tablet computer. Each circle contained a letter of the alphabet, and participants were asked to drag the circles sequentially (in alphabetical order) to the bottom of the square. Each time a circle was dragged to the bottom of the square, a new circle appeared in its original location, continuing the alphabetical sequence (e.g. if letters A-F were on screen, after the A was dragged to the bottom it would be replaced with a G). This continued until all letters of the alphabet from A-Z had been dragged out of the square. Occasionally, new circles initially appeared in blue, orange, or pink, rather than yellow (these were described as 'special circles' in the instructions to participants). These colours correspond with the left, top, and right side of the square respectively. Two seconds after appearing on the screen, their colour then faded to yellow so that they matched the other circles. When a new circle appeared in one of these colours, this represented an instruction that it should eventually be dragged to its corresponding side of the square when it is reached in the sequence. For example, a participant drags A to the bottom of the screen where it disappears. An orange G appears in its place, fading to yellow after 2 seconds. Meanwhile, the participant drags circles B-F to the bottom of the screen, before dragging G to the top. Therefore, a circle temporarily appearing in a non-yellow colour instructed participants to form a delayed intention to drag that circle to a non-standard location when it is eventually reached in the sequence. To remember this instruction, participants could either rely on an internal representation of their intention, or create an external reminder. They created an external reminder by immediately dragging target circles near their instructed location when they appeared on the screen. For example, as soon as an orange G appeared on the screen, the participant could drag this circle to near the top of the square. Then, when they reached G in the sequence its location would remind the participant of their intention. In this case, there was no need to maintain an internal representation of the intended behaviour, seeing as it was directly cued by the circle's position.

One trial consisted of a full 26-letter alphabetical sequence. Within this sequence, a total of 10 target circles appeared, randomly allocated to 10 of the letters from G-Z. This meant that participants needed to remember multiple simultaneous intentions and it was unlikely that they would be able to remember all of them without setting external reminders. The 10 target circles were randomly allocated to the left, top, and right positions of the square. Feedback was provided as follows: when a target circle was correctly dragged to the top, left, or right side of the box, it turned green before disappearing. Otherwise, circles dragged to the top, left, or right turned red before disappearing. When a circle was dragged to the bottom of the box, it turned purple before disappearing regardless of whether it was a target or non-target, which did not provide any feedback. For a demonstration of the task, please visit: http://samgilbert.net/optimalDemo/start.html.

Procedure

The task was performed on a Samsung SM-T580 Galaxy Tab A tablet computer, using the touchscreen interface. Participants were tested individually at the Wellcome Trust Centre for Human Neuroimaging, University College London, UK. Alongside the optimal reminders task, they completed a battery of other tests as part of a larger project investigating the neural basis of metacognitive training. These data will be reported in a separate paper. For the purposes of the present article, we report data from the optimal reminders task alone.

Following a brief practice session, participants performed a total of 17 experimental trials. On some trials participants were forced to use either an internal (unaided memory) or an external (reminder) strategy; on other trials they were free to choose. This allowed us to evaluate choice behaviour using the choice/no-choice method (Siegler & Lemaire, 1997). In order to force an internal strategy, all circles were fixed in position on the screen apart from the next one in the alphabetical sequence, so that target circles could not be moved when they first appeared. In order to force an external strategy, the computer was programmed so that when a target circle appeared, the task could only be continued after the participant moved it within the square. Prior to beginning a forced internal or external trial, participants were informed which strategy they had to use.

Participants were told that they scored points every time they dragged one of the target circles to the instructed location. On trials where they were forced to use an internal or external strategy, they scored 10 points for each correct target response. These conditions occurred on trials 2,4,6,8,10,12,14, and 16, alternating between internal and external conditions so that there was a total of four trials in each condition (with the starting condition counterbalanced between participants, and reversing between the two testing sessions). On the remaining nine trials, participants were given a free choice (see Figure 1, panel B for an example). They could choose to use an internal strategy for the upcoming trial, in which case they scored 10 points per correct target response but were prevented from setting external reminders. Alternatively, they could choose to be permitted to set reminders in the upcoming trial, in which case they were offered a lower number of points for each correct target response. The nine possible values from 1-9 were offered as the lower value in a random order on these trials. Note that the cost of using a reminder in this paradigm is implicit. Participants were offered choices such as 10 points to use their own memory versus 7 points to use reminders, rather than being told that using reminders would cost 3 points. This is because participants may weigh potential gains versus losses differentially due to the well-established phenomenon of loss-aversion (Tversky & Kahneman, 1991). Therefore, we always presented the two options in terms of possible rewards, so that they were more directly comparable.

After each trial, participants were told the total number of points that they had scored in the experiment so far. They were told to try to score as many points as possible, and that on choice trials they should choose whichever strategy they believed would allow them to score more points.

Data analysis

Consider a participant who can correctly respond to an average of 6 out of 10 target circles using an internal strategy, and 10 out of 10 targets if allowed to set external reminders. Given a choice between 10 points per target with an internal strategy and 9 points per target with an external strategy, it is rational to choose the external strategy, because the expected number of points with the internal strategy (10 points x 6 correct responses = 60) is less than the expected number of points with the external strategy (9 points x 10 correct responses = 90). Likewise, if offered 1 point per target using reminders, this would yield an expected score of 10 points per trial, and therefore participants should choose the internal strategy instead. Given a choice between scoring 6 points per target using an external strategy, or 10 points per target using an internal strategy, the expected number of points per trial is identical (i.e. 60). Therefore, an unbiased individual should be indifferent between these two options if offered a value of 6 points per target in the external reminder condition. As this example shows, once we know a participant's mean accuracy when they use each strategy, we can calculate their optimal indifference point, i.e. the value attached to target circles in the external reminder condition that would lead an unbiased individual to be indifferent between the two options. We can then compare this optimal indifference point with their actual indifference point, estimated from their behaviour on choice trials, in order to assess evidence for bias towards one or other strategy. We refer to the difference between the optimal and actual indifference point as the reminder bias.

Our analytic strategy is as follows. First we calculate the mean accuracy (i.e. mean number of target circles correctly dragged to their instructed locations) on forced external trials (ACC_{FE}) and forced internal trials (ACC_{FI}). The expected score on forced internal trials will be 10 x ACC_{FI}, seeing as targets were always worth 10 points on these trials. The optimal indifference point (OIP) is the target value that would lead participants to achieve the same score if they are allowed to use reminders, i.e. OIP x ACC_{FE}. Therefore:

$$OIP \times ACC_{FE} = 10 \times ACC_{FI}$$

Rearranging, this gives:

$$OIP = \frac{10 \times ACC_{FI}}{ACC_{FE}}$$

In order to calculate the actual indifference point, i.e. the value at which participants were equally likely to choose an internal or an external strategy, we calculated the likelihood of choosing an external vs internal strategy across the full range of external target values from 1-9 (Figure 1, panel C). We then fit a sigmoid function to these data using the R package 'quickpsy', bounded to the range 1-9 and otherwise using default parameters. This allowed us to calculate the value associated with a 50% probability of choosing either strategy, according to this function. Note that this approach does not require a monotonic relationship between value and strategy choice, e.g. if participants accidentally chose an external strategy for one of the low-value choices (see Figure 1 panel C for an example). Insofar as participants are unbiased between internal and external strategies, the optimal and actual indifference points should match. If the actual indifference point is higher than the objective indifference point, this would indicate a bias towards internal memory because participants would need to be offered a higher than optimal amount before deciding to use an external strategy. If the actual indifference point is below the objective indifference point, this would indicate a bias towards external reminders because participants would be choosing an external reminder strategy even when offered a value below the level at which it would be optimal to start using reminders.

Optimal and actual indifference points were calculated separately for each participant and session. This is because optimal choice behaviour varies according to each participant's memory abilities. For example, a participant who could score 7/10 with their own memory and 10/10 with reminders should choose an internal strategy if offered 6 points per target to use reminders. But a participant who could score 5/10 with their own memory and 10/10 with reminders would score more points using an external strategy. By investigating the correlation across participants between actual and objective indifference points, we can test whether participants' strategy choices are sensitive to individual differences in memory abilities. Insofar as these two measures are positively correlated, this indicates that participants with the most need for reminders (i.e. those with poorer memory abilities) do indeed choose to use reminders more often.

Results

See Figure 2 for a summary of results. Participants were only able to remember approximately half of the targets using their own memory in the forced internal condition (session 1: M=52.3%, SD=15.4; session 2: M=55.1%, SD=16.0), but nearly all of them when they used external reminders in the forced external condition (session 1: M=94.0%, SD=6.9; session 2: M=97.9%, SD=3.4). Additionally, there was a small improvement in accuracy from session 1 to session 2. The high level of performance in the external condition suggests that memory failures in the internal condition were unlikely to be caused by participants simply failing to notice the colour-change of target circles, seeing as the timings for this colour-change were the same in both conditions. These data were analysed in a 2 x 2 repeated-measures ANOVA with factors Session and Condition, showing significant main effects of Condition ($F(1,40)=455$, $p < 10^{-15}$, η^2_p = .92) and Session ($F(1,40)=9.7$, $p = .003$, $\eta^2_p = .20$), but no significant interaction ($F<1$).

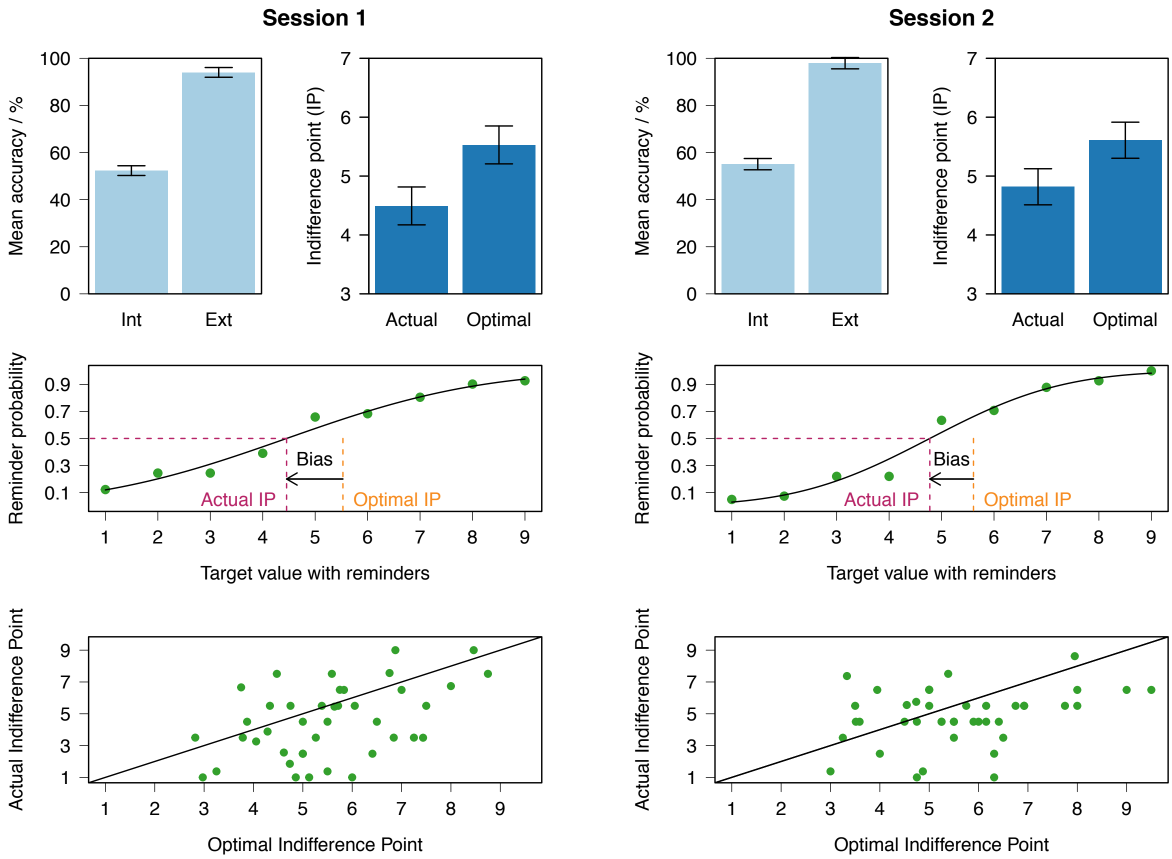

Figure 2. Behavioural results from Experiment 1. Data from session 1 is shown on the left and session 2 on the right. Top row shows mean accuracy in the forced internal (unaided memory) and forced external (reminder) conditions, along with optimal and actual indifference points. Error bars represent within-subject confidence intervals such that nonoverlapping bars indicate p < .05. Middle row shows the likelihood of participants choosing to use reminders when target values from 1-9 were attached to this choice. Mean indifference points (IPs) based on this graph are also shown. Bottom row presents each participant's optimal and actual indifference point. The diagonal line represents perfect calibration between the two (i.e. actual=optimal). Points below this line indicate excessive use of reminders (actual < optimal); points above the line indicate inadequate use of reminders (actual > optimal).

These accuracies imply mean optimal indifference points of 5.5 and 5.6 in the two sessions, however the actual indifference points were lower: 4.5 and 4.8 respectively, indicating excessive use of reminders. In both sessions, this discrepancy between optimal and actual indifference points (i.e. reminder bias) was significant (session 1: $t(40) = 3.25$, $p = .002$, $d = 1.0$; session 2: $t(40) = 2.61$, $p = .013$, $d = .82$), however the bias did not differ significantly between sessions ($t(40) = .76$, $p = .45$, $d = .24$).

In both sessions there were significant correlations between optimal and actual indifference points (session 1: $r = .47$, $p = .002$; session 2: $r = .32$, $p = .045$). Therefore, although participants were biased towards excessive use of reminders, nevertheless individuals who benefitted the most from reminders were more likely to use them. Additionally, there was a significant correlation between the bias scores in the two sessions (r = .47, p = .002; Figure 3).

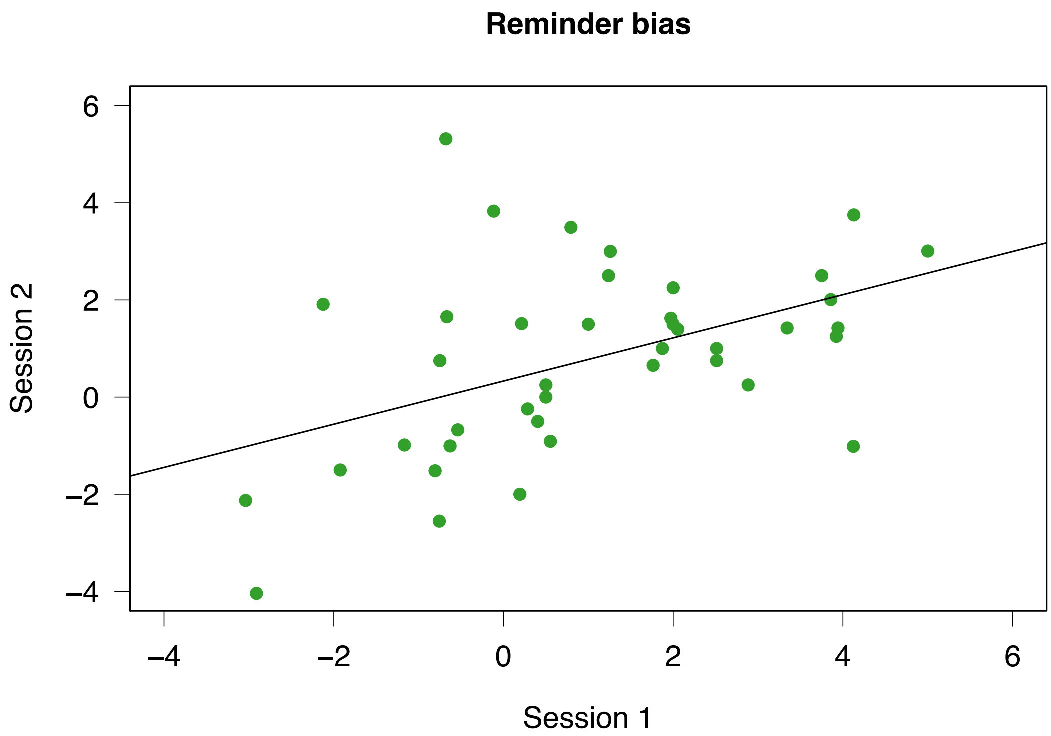

Figure 3. Correlation of bias scores between the two sessions, along with trendline.

In a final set of analyses we investigated the mean duration to complete each trial in the forced internal and forced external conditions. This allows us to test whether it took systematically longer to complete the task using one or the other strategy. In session 1, the mean completion time was significantly longer in the external condition (M=61.2s, SD=10.4s) than the internal condition (M=50.4s, SD=17.8s; t(40) = 3.5, p = .001, d = 1.1). However, there was no significant difference in session 2 (external: M=51.7s, SD=8.5s; internal: M=49.9s, SD=18.2s; t(40) = .58, p =.56, d = .18).

Discussion

This study found clear evidence of bias: in both testing sessions, participants tended to use more reminders than would have been optimal. Despite this significant bias, correlational analyses showed a significant relationship between objective and actual indifference points in the two sessions. This shows that participants who derived the most benefit from reminders also were most likely to use them. Furthermore, bias was also correlated between the two sessions. Therefore, individual biases towards external reminders vs internal memory processes were stable over time.

While the present results show clear evidence for a bias towards external reminders, the cause of this bias is unclear. We can exclude the possibility that participants simply chose the strategy that minimised the time taken to complete the task (Gray et al., 2006), seeing as the preferred external strategy either took longer than the internal strategy (session 1) or the same amount of time (session 2). We can also exclude the possibility that participants' choices were biased due to a form of loss aversion, seeing as the preferred strategy was, if anything, associated with a loss (i.e. reduced reward for each correctly remembered target). However, at least two other explanations remain. One possibility is that the human cognitive system is intrinsically biased away from internal memory processes or cognitive effort, such that individuals would choose a suboptimal strategy (in terms of the reward structure of the task) in order to conform to this bias. We refer to this as the 'intrinsic bias' account. Alternatively (or in addition), individuals might choose sub-optimally due to a metacognitive miscalibration, such that they exaggerate their internal memory limitations regardless of any intrinsic bias towards or away from memory use, tool use, or effort. We refer to this as the 'metacognitive bias' account. The purpose of experiment 2 was to evaluate how well these accounts can explain the results of experiment 1.

Experiment 2

This experiment repeated the procedure of Experiment 1 with three key changes. First, participants earned a payment based on the number of points they scored: they therefore had a direct financial incentive to make optimal choices. This allowed us to test whether participants still show biases, even when they have a clear financial incentive to avoid them. However, it does not distinguish between the intrinsic bias and metacognitive bias accounts, neither of which predicts that a financial incentive would necessarily remove any bias: there is no reason to think that a financial incentive would necessarily remove metacognitive bias, and the intrinsic bias account allows for the possibility that participants may, in effect, accept a financial penalty in return for reduced reliance on internal memory processes or effort. In other words, they would be paying to avoid cognitive effort (see Westbrook et al., 2013 for an example of this). In order to evaluate this possibility, we tested two groups of participants. One group received metacognitive advice as they performed the experiment. They were informed on each trial whether it would be optimal to choose an internal or an external strategy, based on their performance so far. However, it was also emphasised that they were free to choose whichever option they preferred. If participants have an intrinsic bias against cognitive effort (but no metacognitive bias), providing metacognitive advice should not affect this bias. Conversely, if bias towards reminders is caused by metacognitive underconfidence (but no intrinsic bias beyond this), then providing metacognitive advice should eliminate it. We additionally collected metacognitive judgements from participants in this experiment, so that they provided a self-evaluation of how well they could perform the task. This allowed us to test an additional prediction of the metacognitive bias account, that participants' bias towards external reminders should be correlated with their underconfidence in internal memory abilities.

Methods

Participants

108 participants took part in the study (mean age: 31, range 18-80, SD=14.5, 68 female, 40 male). This was based on a power calculation showing that 80% power to detect a between-group difference with medium effect size (d = 0.5) requires at least 102 participants (one-tailed test, seeing as there was a directional hypothesis that providing metacognitive advice should, if anything, reduce bias). This effect size approximately matches the effect size that would be expected for a between-group comparison if the reminder bias shown by participants in session 1 of Experiment 1 was compared with another group where the bias was reduced to zero but the standard deviation was unchanged (d = 0.51). Participants were randomly allocated to two groups: advised (55 participants) and unadvised (53 participants). These groups did not differ significantly in age ($t(95.5)=1.3$, $p = .21$) or gender ($\chi^2 = .02$, $p = .88$). All participants provided informed consent before participating and the research was approved by the UCL Research Ethics Committee.

Procedure

The optimal reminder task was based on experiment 1, with six modifications. First, the trial ordering was adjusted. Rather than interspersing the forced internal and forced external trials throughout the experiment, participants alternated between forced internal and forced external trials for the first eight trials of the experiment (with the condition for the first trial counterbalanced between participants), followed by the nine choice trials. This allowed estimation of each participant's optimal indifference point before the first choice trial. Note that this means that indifference bias scores could potentially be inaccurate, seeing as they no longer control for potential practice effects. However, this would apply to all participants equally, so could not account for any group difference in the reminder bias.

Second, each time that participants in the advised group made a choice between internal and external strategies, they were provided with metacognitive advice. Throughout the experiment, the computer kept track of participants' accuracy when they used internal and external strategies, averaging across all trials (forced and choice). This allowed the optimal indifference point to be calculated, and compared with the target value offered with reminders on choice trials. When participants in the advised group were first instructed about choice trials they were given the following information on the computer screen: "We have been calculating your accuracy on the task so far. This means that we can make a prediction which option is likely to score you most points, based on your performance until now. You will be told this prediction each time you do the task, which may help you to decide whether to do the task with or without reminders. However, you are free to choose whichever option is best - it is completely up to you". On each choice trial they were then given the following information: "According to your performance so far, we have calculated that you will probably score more points if you choose to perform [with/without] reminders. However, you may choose whichever option you prefer." If the target value with reminders was equal to the optimal indifference point, they were told "According to your performance so far, you will score the same number of points regardless of whether you choose to use reminders or not".

A third modification was that we collected participants' metacognitive judgments before the experimental choice trials started. Following the eight forced internal/external trials, they were given the following instructions: "Now that you have had some practice with the experiment, we would like you to tell us how accurately you can perform the task when you do it without using any reminders. Please use the scale below to indicate what percentage of the special circles you can correctly drag to the instructed side of the square, on average. 100% would mean that you always get every single one correct. 0% would mean that you can never get any of them correct". They inputted their answer by dragging a slider on the screen, which displayed the exact percentage they had selected. When they were satisfied with their selection, they were asked "Now, please tell us how accurately you can perform the task with reminders. As before, 100% would mean that you always get every special circle correct. 0% would mean that you can never get any of them correct".

The fourth modification was that participants earned money on the basis of the points scored during the task. They were told that for every 100 points, they would receive £0.30 payment. This translates as performance-related payment of up to £5.10, in addition to a base payment of £5 for taking part.

The fifth modification was that instead of using letters of the alphabet (A-Z) inside the circles, we used numbers (01 – 25) instead. This was because some participants in Experiment 1 reported that they sometimes found it difficult to keep track of the alphabetical sequence. As before, 10 targets were embedded within each sequence.

The final modification was that on each trial a timer was shown on the screen, counting down from three minutes. This encouraged participants to complete the task reasonably quickly. When this was completed, participants undertook some additional tasks as part of a separate project (Bird, Tsai, & Gilbert, in prep), beyond the scope of the present work.

Results

See Figure 4 for a summary of results. Mean trial duration in the forced internal condition (advised group: 56.6s, SD=28.0; unadvised group: M=57.0s, SD=22.1) was similar to the forced external condition (advised group: M=56.3s, 15.8; unadvised group: M=63.7s, SD=22.6; effect of condition: $F(1,106) = 1.6$, $p = .21$, $\eta^2_p = .01$).

As in Experiment 1, accuracy in the forced internal condition (advised group: M=57.5%, SD=16.5; unadvised group: M=54.6%, SD=16.5) was much lower than the forced external condition (advised group: 94.0%, SD=7.2; unadvised group: 92.4%, SD=9.0). These data were analysed in a Condition (forced internal vs forced external) x Group (advised, unadvised) ANOVA, showing a main effect of Condition ($F(1, 106) = 786$, $p < 10^{-15}$, $\eta^2_p =.88$), but no main effect of Group or Group x Condition interaction ($F(1,106) < 1.2$, $p > .28$, $\eta^2_p < .01$). The total number of points scored by the advised group (M=1210, SD=188) was higher than the number of points scored by the unadvised group (M=1171, SD=203), however this difference was not statistically significant ($t(104.7) = 1.0$, $p = .30$, $d = .21$).

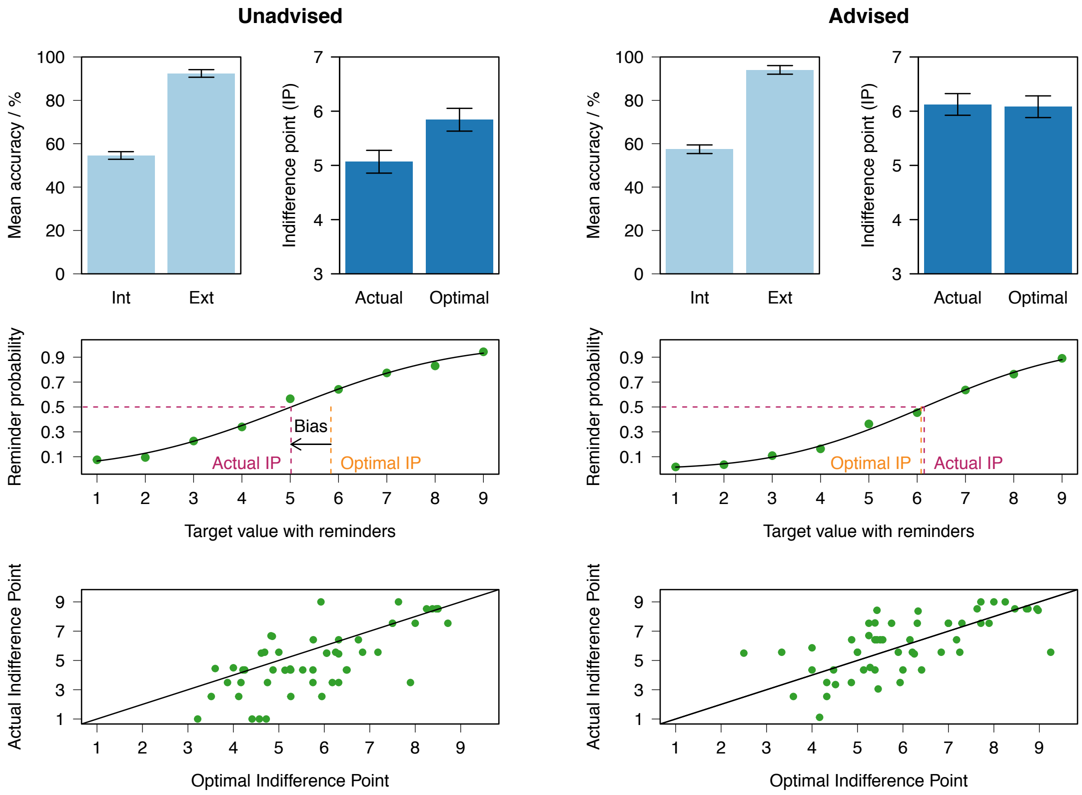

Figure 4. Behavioural results from Experiment 2. Data from the unadvised group is shown on the left and the advised group on the right. Top row shows mean accuracy in the forced internal (unaided memory) and forced external (reminder) conditions, along with optimal and actual indifference points. Error bars represent within-subject confidence intervals such that nonoverlapping bars indicate p < .05. Middle row shows the likelihood of participants choosing to use reminders when target values from 1-9 were attached to this choice. Mean indifference points (IPs) based on this graph are also shown. Bottom row presents each participant's optimal and actual indifference point. The diagonal line represents perfect calibration between the two (i.e. actual=optimal). Points below this line indicate excessive use of reminders (actual < optimal); points above the line indicate inadequate use of reminders (actual > optimal).

In the unadvised group, the optimal and actual indifference points were 5.8 and 5.1 respectively. This discrepancy indicated a significant bias towards reminders, replicating the findings of Experiment 1 ($t(52) = 3.6$, $p = .0008$, $d = .98$). In the advised group, the optimal and actual indifference points were both 6.1 and there was no significant bias ($t(54) = .3$, $p = .73$, $d = .09$). The difference in reminder bias between groups was significant ($t(105) = 2.8$, $p = .003$, $d = .55$; NB this p value is for a one-tailed test, in accordance with the original power calculation). In both groups, the optimal and actual indifference points were significantly correlated (unadvised: $r = .71, p < 10^{-8}$; advised: $r = .67, p < 10^{-7}$).

Turning now to the metacognitive judgements, results are shown in Figure 5. Consistent with earlier studies of prospective memory tasks (Gilbert, 2015b; Meeks et al., 2007; Rummel et al., 2013; Schnitzspahn, Zeintl, et al., 2011), participants were underconfident in their self-judgements of accuracy using internal memory (advised group: $t(54) = 3.6, p < .001, d = .98$; unadvised group: $t(52) = 4.3, p < .0001, d = 1.2$). In addition, participants were underconfident in their self-judgements of accuracy using external reminders (advised group: $t(54) = 3.4, p = .001, d = .93$; unadvised group: $t(52) = 4.45, p < .0001, d = 1.23$). However, the latter predictions are hard to interpret, seeing as they may result from a combination of both participants' general confidence in their own ability to perform the task, along with confidence in the reliability of external support (see Gilbert, 2015b for discussion). The key prediction of the metacognitive bias account is that participants' bias in the choice trials should correlate with their underconfidence in the forced internal condition. This correlation was indeed obtained ($r(51) = -.31, p = .026$; NB the correlation coefficient is negative seeing as underconfidence results in a negative score whereas reminder bias results in a positive score). Therefore, to the extent that participants erroneously believed their internal memory processes to be inadequate, they showed a bias towards external reminders. No such correlation was seen in the advised group ($r(53) = -.02, p = .89$).

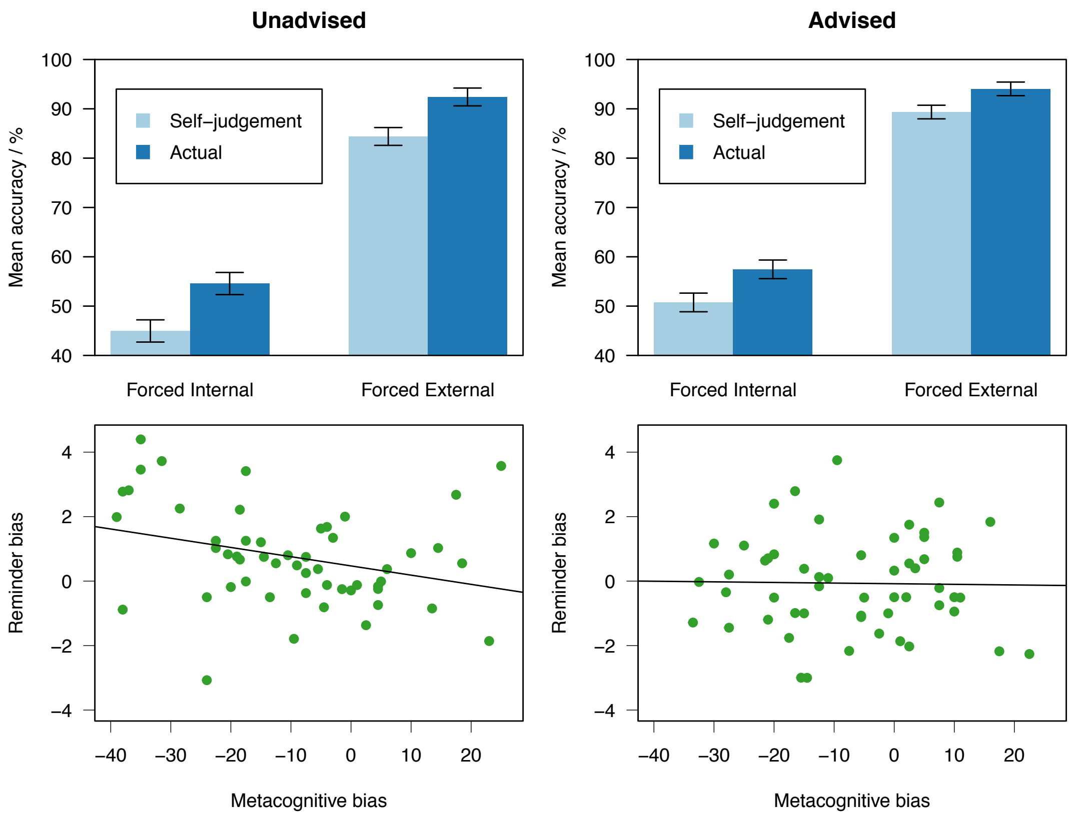

Figure 5. Top: metacognitive judgements of accuracy, along with actual accuracy, in the unadvised (left) and advised (right) groups. Error bars represent within-subject confidence intervals such that nonoverlapping bars indicate p < .05. Bottom: relationship between individuals' metacognitive bias and reminder bias. Metacognitive bias predicts reminder bias in the unadvised group, but not in the advised group.

As demonstrated above, unadvised participants' choice behaviour deviated significantly from optimal, where optimal choices were calculated based on their accuracy in the forced internal and forced external conditions. We also analysed whether their choice behaviour deviated from optimal choice behaviour based on their metacognitive predictions of accuracy in the internal and external conditions rather than objective accuracy. To do this, we calculated each participant's indifference point in the same manner as their objective indifference point but using each participant's self-judged accuracy rather than objective accuracy in the internal and external conditions. This indifference point ($M=5.33$, $SD=2.44$) did not differ significantly from the actual indifference point ($M=5.10$, $SD=2.17$; $t(52) = .74$, $p = .46$, $d = .21$). Therefore, unadvised participants' choice behaviour did not deviate significantly from optimal based on their predictions of their accuracy in the two conditions, but it did deviate from optimal based on their actual accuracy.

Discussion

In participants who were not given metacognitive advice, this experiment replicated the bias towards excessive reminder use seen in Experiment 1. This bias was seen even though there was a financial incentive to behave optimally. However, when metacognitive advice was given, the reminder bias was eliminated. Furthermore, the extent of individuals' reminder bias was predicted by their underconfidence in their internal memory abilities. Both of these findings are consistent with the hypothesis that the reminder bias arises from inaccurate metacognitive evaluation of internal memory abilities.

There was no evidence for an intrinsic bias against internal memory or cognitively effortful processes, seeing as there was no reminder bias in the advised group. Therefore, even if individuals avoid cognitive effort as a default, this bias need not be seen in all circumstances. However, it is unclear whether simply removing metacognitive underconfidence is sufficient to eliminate the bias towards excessive reminders in all circumstances. It could be argued that as well as the elimination of metacognitive error (through the provision of advice), the advised group also had at least two other factors that predisposed them towards unbiased decisions: a) a financial incentive to choose optimally, and b) a reduced cognitive demand, seeing as they could potentially perform the task by accepting advice, without having to deliberate over the correct strategy on each trial. It is possible that without these two factors, individuals might be biased towards reminders even without metacognitive underconfidence. It is also logically possible that there was no influence of metacognitive error on reminder bias at all, and that the difference in bias between the two groups simply reflected the difference in cognitive demand. This would be difficult to reconcile with the correlation between metacognitive error and reminder bias in the unadvised group. However seeing as there were only 53 participants in this group, a sample size at which correlations may be unstable (Schönbrodt & Perugini, 2013), confidence in this finding would be increased if it were replicated in a larger sample.

Experiment 3

This experiment investigated whether it is possible to find metacognitive interventions which influence participants' confidence in their internal memory abilities, and if so whether these interventions have parallel influence on reminder bias. If such a parallel influence were found, this would provide strong evidence for a metacognitive influence on reminder bias, because any variation in reminder bias would be observed without a concomitant difference in cognitive load, unlike Experiment 2. This experiment also allowed us to investigate whether reminder bias can be observed even in the absence of metacognitive underconfidence. Such a finding would suggest that removing underconfidence is not sufficient to eliminate reminder bias, and that other factors (e.g. financial incentive, reduced cognitive demand) need to be present in order to observe unbiased decisions. Thus we investigated two main questions: 1) do interventions that shift metacognitive judgements also shift reminder bias? If so, this provides strong evidence for a metacognitive influence on reminder bias; 2) can reminder bias be observed even in the absence of underconfidence? If so, this shows that metacognitive error cannot explain reminder bias in full.

We manipulated two factors in a between-subject design. The first was feedback valence: half of the participants received positively framed feedback about their performance and the other half received negatively framed feedback. We predicted that negative feedback would make participants less confident in their ability to perform the task (see Raaijmakers, Baars, Schaap, Paas, & van Gog, 2017 for a related finding). The second factor we manipulated was the difficulty of the practice trials: half of the participants began with easy trials and half began with difficult trials, but after this all participants received experimental trials of the same difficulty. We predicted that initially performing an easier version of the task would yield a "metacognitive contrast" effect whereby subsequent trials would seem relatively hard, making participants less confident (see Pansky & Goldsmith, 2014 for a related finding). However, we considered that an opposite effect might also be possible, whereby initially performing a harder version of the task would lead to a "carryover" of decreased confidence, leading to lower confidence on the experimental trials. The key theoretical prediction, regardless of whether increased practice difficulty leads to lower or higher subsequent confidence, was that any manipulation that reduces confidence will make participants more biased towards using reminders (and vice versa). Before commencing data collection we pre-registered our hypotheses, experimental procedure, and analysis plans (http://osf.io/e84p2).

Methods

Participants

As specified in our pre-registered plan, we aimed for a final sample of 67 participants in each experimental group, so that comparisons between groups would have 80% power to replicate the smallest effect reported in the studies of Raaijmakers et al. (2017) and Pansky & Goldsmith (2014). This was an effect size of d = .49 (Raaikmakers et al., 2017, Experiment 2). We tested a total of 315 participants in order to reach our final sample of

268 participants (67 in each group) after applying our pre-registered exclusion criteria. These exclusion criteria were designed to ensure that despite online data collection, outliers were removed and all included participants performed the task with a reasonable level of accuracy and chose strategies rationally (i.e. more likely to set external reminders when this earned more points). Participants were excluded for the following reasons: a) failing to show increased accuracy in the forced external than the forced internal condition (n=17); b) lower than 10% accuracy in the forced internal condition (n=5); c) lower than 70% accuracy in the forced external condition (n=12); d) negative correlation between target value and likelihood of choosing to use reminders, suggesting random or counter-rational strategy choice behaviour (n=6); reminder bias score more than 2.5 standard deviations from the group mean (n=5); metacognitive bias score more than 2.5 standard deviations from the group mean (n=2). The final sample had mean age 37 (range=21-70; SD=11; 152 male, 115 female, 1 other).

Procedure

Participants were recruited from the Amazon Mechanical Turk website to take part in the experiment, completing the tasks using their computer's web browser (for a demonstration, see: "http://www.ucl.ac.uk/sam-gilbert/CS1/Demo/WebTasks.html") We restricted participants to those located in the USA to reduce variability. The experimental task was akin to the one used in Experiment 2 in the sense that each trial involved 25 numbered circles rather than using letters. In most other respects the procedure was identical to Experiment 1 (e.g. forced internal and forced external trials were interspersed amongst the following sequence of 17 trials, to control for practice effects). However, the following modifications were made from the earlier experiments:

First, participants received a feedback screen after each trial. For example, participants in the positive feedback condition might receive a message such as "Well done – excellent work! You responded correctly to most of the special circles", whereas a participant in the negative feedback condition might receive a message such as "Room for improvement. You got some of the special circles wrong" (for a full description of the feedback, see Table 1). Importantly, although this feedback was framed differently between the positive and negative conditions, it was always veridical and did not deceive participants.

Second, we manipulated the difficulty of the practice trials. Prior to commencing the experimental trials, participants performed five trials that contained either 4 targets (easy-practice condition) or 16 targets (difficult-practice condition). Following this, they were told that the task would now get more difficult (easy-practice condition) or easy (difficult-practice condition). They were also told: "It will stay like this for the rest of the experiment. Please ignore the difficulty of the practice trials you have just done and remember that the task will be like this from now on".

After a further trial containing 10 targets (which was the standard procedure from now on), they were asked to provide a metacognitive judgement of their unaided ability to perform the task with the following instructions: "Now that you have had some practice with the experiment, we would like you to tell us how accurately you can perform the task. Please ignore the earlier practice trials and just tell us how accurately you can do the task when it is the same difficulty as the trial you have just completed. The difficulty will stay the same as this for the rest of the experiment. Please use the scale below to indicate what percentage of the special circles you can correctly drag to the instructed side of the square, on average. 100% would mean that you always get every single one correct. 0% would mean that you can never get any of them correct." After this, participants were introduced to the offloading strategy, the procedure for scoring points, and choosing whether or not to use reminders, in the same manner as Experiment 1. Then they completed the 17 experimental trials.

Participants were randomly allocated into four groups, crossing the factors of feedback valance and practice difficulty. Like Experiment 1 (but not Experiment 2), points were not linked to any financial reward, and all participants received a flat payment of $7.50 for taking part.

Accuracy	Feedback (Positive condition)	Feedback (Negative condition)
0%	You did not get any special circles correct this time.	Room for improvement. You got all of the special circles wrong.
Above 0%, below 50%	Well done – good work! You are responding well to the special circles.	Room for improvement. You got most of the special circles wrong.
Above 50%, below 100%	Well done – excellent work! You responded correctly to most of the special circles.	Room for improvement. You got some of the special circles wrong.
100%	Well done – perfect! You responded correctly to all of the special circles.	You did not get any of the special circles wrong this time.

Table 1. Feedback provided in the positive and negative conditions.

Results

	Easy practice, positive feedback	Easy practice, negative feedback	Difficult practice, positive feedback	Difficult practice, negative feedback
Forced external % correct	96.6 (4.8)	95.9 (5.9)	97.7 (4.1)	96.9 (5.7)
Forced internal % correct	56.5 (16.2)	58.2 (19.4)	59.2 (17.0)	60.6 (19.6)
Mean confidence	65.9 (23.2)	52.5 (26.8)	53.1 (29.1)	49.1 (34.9)
Metacognitive bias	9.3 (27.2)	-5.6 (28.4)	-6.2 (29.5)	-11.4 (36.7)
OIP	5.8 (1.6)	6.0 (1.9)	6.1 (1.7)	6.2 (1.9)
AIP	4.7 (2.5)	4.2 (2.5)	4.2 (2.6)	3.4 (2.8)
Reminder bias	1.2 (2.7)	1.8 (2.4)	1.9 (2.0)	2.9 (3.1)

Table 2. Behavioural results from Experiment 3, in each of the four groups. Table shows means with standard deviations in parentheses. OIP = optimal indifference point; AIP = actual indifference point.

See Table 2 for a summary of results. We first investigated accuracy in the forced internal and forced external conditions, in a mixed ANOVA with factors Condition (internal, external), Practice-Difficulty (easy, difficult), and Feedback-Valence (positive, negative). There was a significant main effect of Condition ($F(1,264) = 1380$, $p < .0001$, $\eta^2_p = .84$), but the effect of the Practice-Difficulty and Feedback-Valence manipulations, and their interactions, were all non-significant ($F(1,264) < 2.1$, $p > .15$, $\eta^2_p < .01$). Therefore, while using reminders significantly increased accuracy (as in the earlier experiments), there was no significant influence of the metacognitive interventions on task performance.

Next, we investigated metacognitive judgements by subjecting participants' predicted unaided accuracy to an ANOVA with factors Practice-Difficulty and Feedback-Valence. There were significant main effects of both Practice-Difficulty ($F(1,264) = 5.3$, $p = .02$, $\eta^2_p = .02$) and Feedback-Valence ($F(1,264) = 6.0$, $p = .02$, $\eta^2_p = .02$), but no significant interaction ($F(1,264) = 1.8$, $p = .18$, $\eta^2_p < .01$). Participants' confidence was increased if they had easier practice trials, and/or positive feedback. We also investigated participants' metacognitive bias, that is, the difference between their metacognitive prediction and actual accuracy in the forced internal condition. This bias score also showed significant main effects of Practice-Difficulty ($F(1,264) = 8.0$, $p = .005$, $\eta^2_p = .03$) and Feedback-Valence ($F(1,268) = 7.2$, $p = .007$, $\eta^2_p = .03$) but no significant interaction ($F(1,264) = 1.7$, $p = .20$, $\eta^2_p < .01$). We compared each group's bias score against zero with one-sample t-tests, which showed that participants in the Easy, Positive group were significantly over-confident (i.e. their predicted accuracy levels were significantly greater than actual accuracy; $t(66) = 2.8$, $p = .007$, $d = .69$). Predicted accuracy was slightly underconfident but not significantly different from zero in the Easy, Negative ($t(66) = 1.6$, $p = .11$, $d = .40$) and Difficult, Positive ($t(66) = 1.7$, $p = .09$, $d = .42$) groups. Participants in the Difficult, Negative group were significantly underconfident ($t(66) = 2.5$, $p = .013$, $d = .63$).

We investigated the reminder bias in a similar manner to metacognitive bias. There were significant main effects of both Practice-Difficulty ($F(1,264) = 7.9$, $p = .005$, $\eta^2_p = .03$) and Feedback-Valence ($F(1,264) = 6.5$, $p = .01$, $\eta^2_p = .02$), but no significant interaction ($F(1,264) = .4$, $p = .53$, $\eta^2_p < .01$). One-sample t-tests showed that participants in all four groups were significantly biased towards excessive use of reminders ($t(55) > 3.5$, $p < .001$, $d > .87$ in each group). However, the bias was more than twice as large in the Difficult, Negative group than it was in the Easy, Positive group. The relationship between metacognitive bias and reminder bias, in each of the four groups, is shown in Figure 6.

In order to investigate the relationship between metacognitive bias and reminder bias, we conducted a linear regression analysis with a dependent variable of the reminder bias and the following factors: Practice-Difficulty, Feedback-Valence, Practice-Difficulty x Feedback-Valence interaction, and metacognitive bias. This showed a significant effect of metacognitive bias ($\beta = -.029$, $SE = .005$, $t(263) = 5.8$, $p < 10^{-7}$), providing strong evidence that the reminder bias is related to metacognitive bias, even after statistically controlling for any direct influence of the metacognitive interventions. However, in this analysis there was no longer a significant effect of practice difficulty ($\beta = .29$, $SE = .15$, $t(263) = 1.9$, $p = .054$) or feedback valence ($\beta = .26$, $SE = .15$, $t(263) = 1.7$, $p = .09$), nor was the practice difficulty x feedback valence interaction significant ($\beta = .17$, $SE = .15$, $t(263) = 1.1$, $p = .26$). Therefore, there was no longer a direct effect of the metacognitive interventions on reminder bias when metacognitive judgements were included in the model. We additionally conducted a pair of mediation analyses using PROCESS (Hayes, 2017), investigating practice difficulty and feedback valence separately. Unlike the analyses above, these were not included in our pre-registered analysis plan. The analyses showed a significant indirect effect on reminder bias of both practice difficulty ($\beta = .16$, $SE = .06$, $Z = 2.5$, $p = .01$) and feedback valence ($\beta = .15$, SE

= .06, Z = 2.4, p = .02), mediated by metacognitive judgements. Given that the direct influence of these interventions on reminder bias were nonsignificant, these results suggest that their effects were fully mediated by their influence on metacognitive judgements.

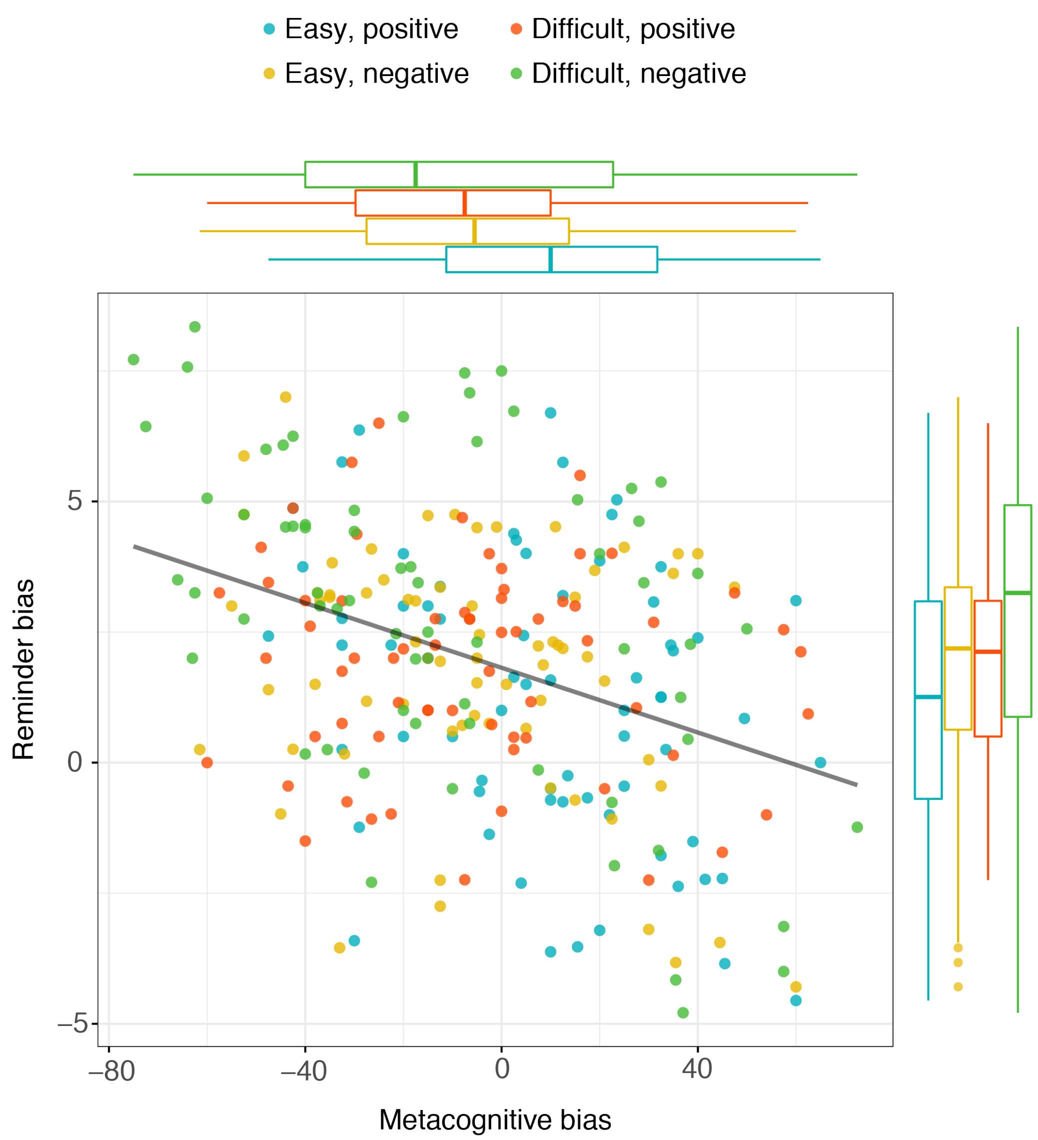

Figure 6. Relationship between metacognitive bias and reminder bias in the four groups. Horizontal margin shows boxplots for the metacognitive bias in each group, and vertical margin shows boxplots for the reminder bias. Grey line indicates linear regression for the relationship between the two variables, across all participants.

Discussion

Both practice difficulty and feedback valence influenced participants' metacognitive beliefs about their memory abilities, without influencing actual performance levels. These effects were accompanied by parallel shifts in participants' reminder bias, which were significantly mediated by metacognitive judgements. Insofar as a manipulation made participants less confident in their memory, it made them more biased towards reminders. We also found a significant relationship between individuals' metacognitive and reminder biases, replicating a similar result from the unadvised group of Experiment 2. These findings strongly support the hypothesis that metacognitive judgements influence individual biases towards or away from external reminders, and that metacognitive interventions can modify such biases.

A second question addressed in this experiment was whether metacognitive biases are sufficient to explain the reminder bias. We found that one group of participants (Easy, Positive) was significantly overconfident in its metacognitive judgements, while another group (Difficult, Negative) was significantly underconfident. However, both groups were biased towards external reminders, albeit with the bias in the latter group being more than twice as large as the former. This shows that metacognitive underconfidence is not necessary in order to observe a reminder bias, seeing as it is possible to see a bias towards reminders even in participants who are overconfident in their memory abilities. Therefore, our results show that metacognitive judgements contribute to the reminder bias, but the bias cannot be exhaustively explained by metacognitive error.

General Discussion

Cognitive tools such as external reminders carry both costs (e.g. the time/effort spent setting them up) and benefits (e.g. the increased likelihood of remembering). In this study we investigated how optimally participants weigh such costs and benefits by giving them a free choice between earning a maximum reward for each remembered item using their own memory, or a lesser reward using external reminders. Participants chose to set external reminders more often than would be optimal, even when they had a financial incentive to choose optimally. This reminder bias was large in magnitude (Cohen's d > 0.8 each time the bias was observed) and individual differences were stable over time. Participants' metacognitive evaluations of internal memory abilities predicted these individual differences, and the bias was eliminated when participants were provided with metacognitive advice that specified which decision was likely to be optimal. We therefore conclude that individuals show systematic biases in their use of external cognitive resources versus internal processes, and these biases are related to metacognitive judgements of confidence (consistent with the metacognitive model of cognitive offloading presented by Risko & Gilbert, 2016). We also found that bias cannot be exhaustively explained by metacognitive error, i.e. the discrepancy between predicted and actual ability, seeing as it could be observed in the context of both under- and over-confidence. Therefore other factors such as a preference to avoid cognitive effort may play a role too.

These results have clear practical implications regarding the use of cognitive tools in everyday life. With the advent of modern technology, we have continual opportunities to offload cognitive processes into external devices. However, it is clearly not optimal to always do so, leading necessarily to cost/benefit decisions. For example, it would not be optimal to set reminders for every activity that we intend to do, regardless of its importance or the likelihood that we would remember it anyway (e.g. to eat, sleep, or perform activities that are part of well-established daily routines). Our results suggest that individuals may make such cost/benefit decisions suboptimally as a result of metacognitive error. They also suggest that such decisions may be improved if methods could be found to improve individuals' metacognitive accuracy.

In many cases, over-use of a cognitive tool will not lead to any harmful effects. However, in some safety-critical fields over-reliance on an external tool can have disastrous consequences. In one case, aeroplane pilots trusted the ability of the autopilot and failed to intervene and take manual control, even as the autopilot crashed the Airbus A320 they were flying; in another, an automated cruise ship navigation system malfunctioned and the crew failed to intervene, allowing the ship to drift off course for 24 hours before it ran aground (Lee & See, 2004). As a result of cases like these, researchers in the field of human factors have paid particular attention to the phenomenon of 'automation complacency' (insufficient monitoring of whether an external tool is operating adequately) and 'automation bias' (individuals' excessive trust in the capabilities of automatic tools; see Parasuraman & Manzey, 2010 for a review). It has been hypothesised that trust (in the abilities of an external tool) and confidence (in one's own abilities) are key factors driving such biases (Lee & See, 2004). The present results directly support this view (see Weis & Wiese, 2019, for further supporting evidence).

We found that bias was eliminated in the advised group of Experiment 2. However, participants in Experiment 3 were biased towards reminders regardless of whether their metacognitive judgments were under- or over-confident. Therefore, while participants in Experiment 3 were biased towards reminders regardless of metacognitive error, participants in Experiment 2 were unbiased as long as metacognitive advice was provided. How might this difference be explained? One possibility is that participants had a financial incentive to behave optimally in Experiment 2, but not Experiment 3. Therefore, in order to remove reminder bias it may be necessary to ensure the removal of metacognitive error *and* to provide a strong incentive to behave optimally according to the reward structure of the task, otherwise a preference to avoid cognitive effort might prevail. A second possibility is that participants in the advised group of Experiment 2 had a reduced cognitive load, in the sense that they could always default to the advised option rather than performing a cost-benefit analysis on every trial. Participants might choose more optimally under conditions of low cognitive load, however in the context of higher cognitive load it may be more rational to choose options that minimise further cognitive load. This would be consistent with the "meta-decision making" framework proposed by Boureau et al. (2015). Regardless of the explanation of this discrepancy between Experiments 2 and 3, our results show 1) that metacognitive error is one factor that can influence reminder bias, and 2) that reminder bias cannot be explained by metacognitive bias alone. Thus, even though reminder bias cannot be exhaustively be explained by metacognitive error, it is nevertheless important to consider the role of metacognitive factors in effort allocation. For example, the reminder bias in Experiment 3 was more than doubled by metacognitive interventions that influenced participants' confidence. These results imply that individuals may sometimes fail to expend cognitive effort not due to an intrinsic bias against doing so, but rather as a result of failing to adequately predict the positive outcomes that would be expected to arise from self-performance (cf Shenhav, Botvinick, & Cohen, 2013).

As well as metacognitive bias, another possible source of bias towards external reminders is a preference to avoid variability in performance. That is, participants might avoid an internal memory strategy because it results in higher variability in accuracy, even in situations where it results in higher mean accuracy as well. This would be consistent with recent research showing that participants are risk-averse with respect to mental effort, preferring a fixed amount of effort to a variable amount, even when the mean is matched (Apps, Grima, Manohar, & Husain, 2015). While this seems plausible, we have no direct evidence for this possibility. Nor can this account explain the relationship between metacognitive bias and reminder bias in Experiments 2 and 3, or the effect of providing metacognitive advice.

In the present study, participants were underconfident about their internal memory abilities (apart from the Easy, Positive group in Experiment 3) and over-used reminders. Underconfidence is the pattern generally found in laboratory studies of prospective memory (Gilbert, 2015b; Meeks et al., 2007; Rummel, Kuhlmann, & Touron, 2013; Schnitzspahn et al., 2011). However, in other situations individuals' metacognitive judgements (and hence cost/benefit decisions) may be biased in the opposite direction, potentially including naturalistic prospective memory tasks executed in everyday life. This might especially be the case if the time and/or effort cost of setting reminders is larger than the minimal cost incurred here. The experimental tasks used here clearly differ from naturalistic prospective memory in several respects. One obvious difference is that the interval between encoding and retrieving intentions was just a few seconds in the present study, but everyday prospective memory unfolds over a much wider timescale. This could lead to overconfidence in naturalistic prospective memory tasks, seeing as individuals may underestimate the way that intentions currently maintained at a high level of activation may fade over time. Another difference between the present tasks and naturalistic PM is that the experimental task was extremely difficult, with participants only achieving approximately 50% accuracy using their own memory. Even in the absence of reminders, many naturalistic PM tasks will have higher chances of success than this. Previous studies suggest that underconfidence is particularly pronounced in more difficult tasks (Cherkaoui & Gilbert, 2017; Gilbert, 2015b; though see Rummel et al., 2013). Therefore it is possible that individuals would be underconfident in laboratory tasks but overconfident in naturalistic ones, which could lead to inadequate use of reminders in everyday life. Direct evidence for this possibility comes from a study by Devolder et al. (1990), showing that participants were overconfident in a naturalistic PM task (making a series of telephone calls over a 4-week period), in contrast to the underconfidence found in the laboratory studies reviewed above.

As well as differing between tasks, biases might also differ between individuals. Indeed, Experiment 1 showed a significant correlation between reminder biases between two sessions 2 weeks apart (though it should be noted that the sample size for this analysis was relatively low at N=41). This shows that individuals may have idiosyncratic biases towards or away from cognitive tools, which may require personalised interventions to correct. In addition, biases may differ systematically between different groups. For example, individuals with acquired brain injury may fail to update metacognitive evaluations of their abilities (acquired through a lifetime of experience) to the post-injury reality. This is directly supported by Knight et al. (2005) who found that patients with traumatic brain injuries were overconfident about their prospective memory performance whereas healthy controls were underconfident. This overconfidence could lead to inadequate use of external aids, underlining the importance of improving 'insight' during neuropsychological rehabilitation (Cicerone et al., 2000; for further discussion see Fleming et al., 2017; Shum, Fleming, Gill, Gullo, & Strong, 2011). Conversely, healthy ageing may be associated with an opposite bias, which may be associated with underconfidence in one’s memory abilities (Touron, 2015). This could confer a compensatory effect, seeing as it would lead to increased use of reliable external resources, and hence improved functional outcomes. Such an effect may go some way towards explaining the phenomenon that older adults tend to underperform younger adults in laboratory prospective memory tasks (where reminders are generally not permitted), but perform similarly or better than young adults in naturalistic tasks where external resources can be used (Schnitzspahn, Ihle, Henry, Rendell, & Kliegel, 2011). However, this phenomenon is likely to be complex and cannot be attributed only to increased use of external aids by older adults (see Maylor, 2008; Phillips, Henry, & Martin, 2008 for discussion).

As a result of these considerations, we do not propose that excessive use of reminders and external tools will always be seen, across all tasks, populations, and individuals. Rather, we propose that biases may be seen in either direction, due (at least in part) to erroneous metacognitive evaluations. Regardless of the direction of the error, our results suggest that improving metacognitive calibration may promote effective use of cognitive tools, and hence improved functional outcomes in everyday life. As shown by Experiment 2, behavioural biases may be mitigated if individuals are provided with metacognitive advice and feedback, indicating the likely outcomes of trying to accomplish a task using internal cognitive resources alone versus a cognitively extended strategy. One particular issue when it comes to naturalistic prospective memory is that there is typically a long delay between A) the metacognitive evaluation of one's memory abilities when a strategic decision is made about how to remember an intention, and B) the subsequent feedback as to whether that strategy was effective. For example, suppose that an individual forms an intention at a particular time and decides that a reminder will not be necessary. They may find that they later forget the intention, however this will be temporally remote from the original decision and therefore may not present a clear learning signal to improve subsequent metacognitive evaluations. It may be particularly valuable, therefore, to find methods by which prospective memory success or failure can be used to deliver clear feedback with respect to the original metacognitive evaluations and strategy choices, as a learning signal to improve future decisions (see Carpenter et al., 2019 for evidence that training can improve metacognitive judgements).

In conclusion, we found evidence in this study for strong, stable biases in individuals' use of external cognitive tools versus internal resources. These biases are predicted by metacognitive beliefs, can be modified by metacognitive interventions, and eliminated by providing metacognitive advice. Understanding the sources of these biases, and interventions to mitigate them, can improve functional outcomes as our cognitive systems become increasingly enmeshed with external tools and resources.

Context

This work originated from earlier studies investigating circumstances under which participants decide to set external reminders for delayed intentions (Gilbert, 2015a), and the metacognitive influences on those decisions (Boldt & Gilbert, 2019; Gilbert, 2015b). We wished to go beyond these earlier studies and develop a paradigm to investigate the optimality of offloading decisions. Having established this new paradigm in the present article, we consider that the following questions may be of particular interest: 1) Previous work has shown that offloading behaviour differs in older adults (Gilbert, 2015a) and young children (Redshaw et al., 2018), compared with young adults. To what extent do effects such as this reflect a rational response to altered unaided ability to remember, versus a shift in the bias towards or away from reminders? 2) What interventions can be developed to alter participants' bias towards or away from cognitive offloading, beyond those established in Experiment 3? 3) To what extent are biases towards or away from cognitive offloading domain-general versus domain-specific? 4) What light can this paradigm shed on the processes by which participants regulate the allocation of cognitive effort, and the relationship between these processes and metacognitive evaluations?

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