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Problem Solvers Adjust Cognitive Offloading Based on Performance Goals

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Abstract

When incorporating the environment into mental processing (*cf.*, *cognitive offloading*), one creates novel cognitive strategies that have the potential to improve task performance. Improved performance can, for example, mean faster problem solving, more accurate solutions, or even higher grades at university.[1] Although cognitive offloading has frequently been associated with improved performance, it is yet unclear how flexible problem solvers are at matching their offloading habits with their current performance goals (can people improve *goal-related* instead of generic performance, e.g., when being in a hurry and aiming for a “quick and dirty” solution?). Here, we asked participants to solve a cognitive task, provided them with different goals —maximizing speed (SPD) or accuracy (ACC), respectively—and measured how frequently (Experiment 1) and how proficiently (Experiment 2) they made use of a novel external resource to support their cognitive processing. Experiment 1 showed that offloading behavior varied with goals: Participants offloaded less in the SPD than in the ACC condition. Experiment 2 showed that this differential offloading behavior was associated with high goal-related performance: fast answers in the SPD, accurate answers in the ACC condition. Simultaneously, goal-unrelated performance was sacrificed: inaccurate answers in the SPD, slow answers in the ACC condition. The findings support the notion of humans as canny offloaders who are able to successfully incorporate their environment in pursuit of their current cognitive goals. Future efforts should be focused on the finding’s generalizability, for example, to settings without feedback or with high mental workload.

Keywords: Cognitive offloading; Distributed cognition; Problem solving; Strategy selection; Extended cognition

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1. Introduction

Saving a door code on the smartphone, outsourcing arithmetic to a calculator, or relying on cloud-based rather than brain-based knowledge: The contemporary ubiquity of computerized equipment has considerably increased the availability of external strategies to support human cognizing (e.g., Clark, 2004; Clowes, 2013; Dror & Harnad, 2008). Such incorporation of external resources into the cognitive repertoire can be quite rewarding as it can change a cognitive task's cost structure (Kirsh, 2010) and, if used wisely, improve task-related performance. In other words, internal and external strategies are associated with distinct performance profiles[2] (e.g., Lemaire & Lecacheur, 2001; Risko, Medimorec, Chisholm, & Kingstone, 2014; Siegler & Lemaire, 1997; Touron & Hertzog, 2014; Walsh & Anderson, 2009), which makes it important to choose the right strategy at the right time. For example, outsourcing arithmetic to a calculator can be superior to mental processing because the former might afford increased speed and accuracy with respect to the latter (Siegler & Lemaire, 1997). In general, it was found that humans frequently (e.g., Gray, Sims, Fu, & Schoelles, 2006; Lemaire & Lecacheur, 2001; Walsh & Anderson, 2009)—though not always (Gilbert et al., ; e.g., Risko & Dunn, 2015; Touron, 2015; Weis & Wiese, 2019)—show high proficiency in mixing internal and external cognitive strategies. However, there is currently no consensus in the literature as to how humans achieve this proficiency (Anderson, 1990; Kirsh, 2013; Marewski & Schooler, 2011; Risko & Gilbert, 2016, p. 685; Scaife & Rogers, 1996).

In this paper, we focus on a hitherto neglected antecedent of a problem solver's decision to use an external strategy: performance goals. Affording the pursuit of a user's goal is a hallmark of humane technology; without it, a device would not empower but rather distract its users from what is important to them (Bosker, 2016). To shed light onto this topic of societal relevance, we used this study to ask whether human problem solvers possess the skills to pursue their goals in technologically enhanced environments.

1.1. Cognitive offloading: Using the environment to (help us) think

The general idea of using cognitive strategies that incorporate a problem solver's environment to decrease brain-based processing costs is subsumed under the term *cognitive offloading* (Risko & Gilbert, 2016; for a review). Cognitive offloading overlaps with other approaches that also expand cognitive science's classic focus of what's happening inside the brain and include body (*Embodied Cognition*; e.g. Wilson, 2002) and environment (*Situated Cognition*; e.g. Kirsh, 2009; *Extended Cognition*; e.g. Clark & Chalmers, 1998; and *Distributed Cognition*; e.g. Hollan, Hutchins, & Kirsh, 2000).[3] A related concept has been termed *epistemic action*, which is defined as an action undertaken to advance in a cognitive task rather than to alter the physical environment for non-cognitive purposes (Kirsh & Maglio, 1994).[4] It should be noted that cognitive offloading can constitute very simple operations like replacing brain-based with paper-based retrieval or complex and dynamic operations like the ones that take place when a pilot is interacting with an airplane's cockpit (Hutchins, 1995). To reduce complexity, this paper focuses on the former rather than the latter.

1.2. Are the problem solver's goals considered in the decision to offload cognition?

Goal-efficiency set aside, many studies suggest that human problem solvers are quite proficient in deciding when to offload cognition. For example, human problem solvers were shown to stop using external resources with high access costs (Gray et al., 2006; Walsh & Anderson, 2009), increase offloading with increased difficulty of the cognitive task (Experiment 5: Risko & Gilbert, 2016; Risko et al., 2014; Walsh & Anderson, 2009), decrease offloading if the external resource is unreliable (Weis & Wiese, 2019), and are able to adjust a computer program based on their own memory capabilities (Howes, Duggan, Kalidindi, Tseng, & Lewis, 2016).

What is unclear at this point is whether humans are adaptive enough to adjust offloading based on their current goals. In most studies, only task difficulty (e.g., Risko & Dunn, 2015; Risko et al., 2014; Walsh & Anderson, 2009; Weis & Wiese, 2019) or accessibility of the external resource (e.g, Gray et al., 2006; Walsh & Anderson, 2009) was manipulated. Consequentially, they have not been sufficient to silence concern in the public (e.g., Bowles, 2018; Lewis, 2017) and the academic community (e.g., Risko & Dunn, 2015; Turkle, 2012; Weis & Wiese, 2019) about whether people are able to recruit external resources "for their own good." This concern seems reasonable because it can be hard to gauge whether seemingly proficient behavior is related to the problem solver's current needs and goals. That is, even though the way people use external resources might maximize speed (Gray et al., 2006) or monetary reward (Walsh & Anderson, 2009), it is hard to gauge whether that person's priority was to optimize for the respective metric in a goal-oriented manner (i.e., time or money, respectively) or used a generic cognitive processing approach instead (e.g., maximizing speed irrespective of current goals; Gray et al., 2006). People do aim to optimize different metrics in the same task (e.g., effort and accuracy; Risko & Dunn, 2015) and retroactively determining that metric is difficult. Lastly, problem solvers frequently prioritize local over global performance (Fu & Gray, 2006), making it difficult to infer whether poorly performing participants were unable to pursue their performance goals, pursued local rather than global goals, or had performance-independent goals like minimizing effort.

To make informed conclusions about the importance of problem solvers' goals for their decision to offload cognition, it is thus imperative to clearly communicate and manipulate these goals. Such informed conclusions are currently not available but would be highly valuable as they provided insight into how adaptively a human problem solver can navigate the cognitively enhanced environments of today and tomorrow.

1.3. Current investigation

In this study, we controlled for well-established contributors to cognitive strategy selection (i.e., task difficulty and properties of the external resource) to investigate whether problem solvers are adaptive enough to adjust cognitive offloading based on their current goals. For this purpose, a novel human-computer-interaction paradigm has been developed (see Section 2.1.1). Specifically, we provided participants with different performance goals and tracked whether they differed in how frequently they recruited an external resource (Experiment 1) and whether they were able to mix internal and external resources in a way compatible with their current goals (Experiment 2). If internal and external strategies differed in their goal-related performance profiles, we would expect participants to employ differential offloading behaviors when confronted with differential performance goals (*H1*, Experiment 1). This differential offloading behavior should be exhibited despite the availability of identical internal and external resources. Furthermore, if differential offloading behavior is exhibited, we expect it to be associated with performance benefits specifically related to the current performance goal (*H2-1*) while possibly being associated with performance detriments related to performance metrics not relevant for the current goal (*H2-2*; Experiments 2A and B). The hypotheses are described in more detail in the first paragraphs of Sections 2 and 3.

2. Experiment 1: Free choice

Experiment 1 was conducted to investigate whether problem solvers employ differential offloading behaviors when confronted with differential performance goals (*H1*): In the accuracy goal condition, participants were incentivized for answering correctly; in the speed goal condition, participants were incentivized for answering fast.

2.1. Methods and materials

In total, 100 participants were recruited and assigned equally to an accuracy *performance goal* and a speed *performance goal* group. The final sample that entered data analysis consisted of 88 students (47 accuracy, 41 speed *performance goal*). More information on participants, apparatus, stimuli, procedure, and data filtering can be accessed in Data S1. Data and R analysis script are available through the Open Science Framework at https://osf.io/sh6qa/.

2.1.1. Extended rotation task

During each trial, participants had to engage in an expansion of the mental rotation paradigm (Shepard & Cooper, 1986; see also Shepard & Metzler, 1971), a task we termed *Extended Rotation Task* (see Fig. 1; see Weis & Wiese, 2018, 2019). In the original paradigm by Shepard and Metzler, the cognitive processes necessary to solve the task rely on mental resources only. In our expanded paradigm, computer-based external resources can be used to outsource the mental rotation part of these cognitive processes (see Fig. 1a). Designing the external resource in a way that it affords offloading one specific cognitive process minimizes variance in usage behavior and sets the stage for researching physiological correlates in future studies.

2.1.2. Study design

The study follows a three-factorial design with the within-participants factors *handedness* of the working stimulus with respect to the base stimulus (same, opposite; Fig. 1b) and *angle* (0°, 60°, 120°, 180°; Fig. 1b), and the between-participants factor *performance goal*

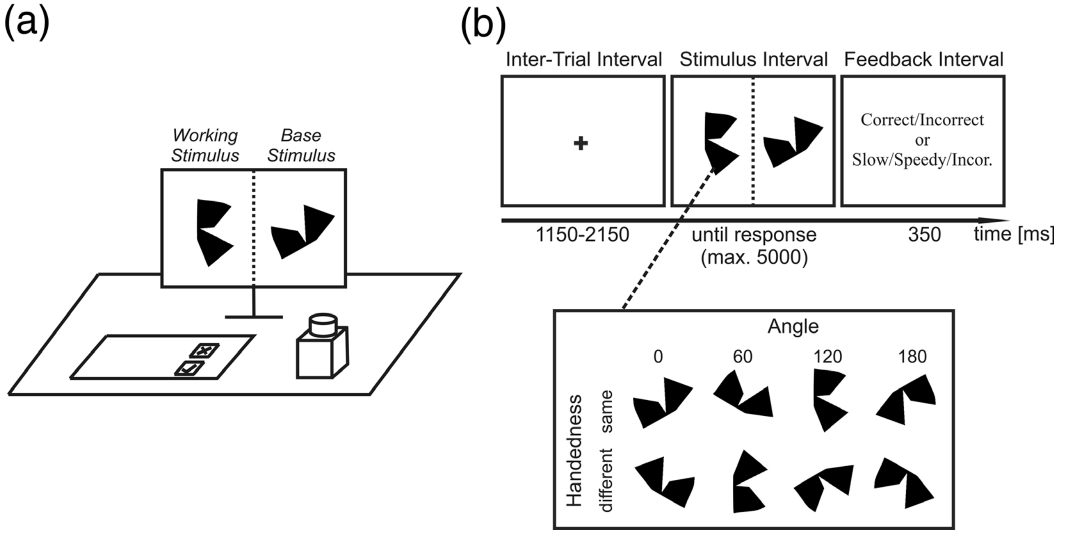

Fig. 1. Extended rotation task. Participants have to compare the handedness of two stimuli that differ in their angular orientation and decide whether the left is the "same" (only rotated in 2D plane) or a "different" (first mirrored, then rotated in 2D plane) stimulus. For each shape, the base stimulus stays identical, whereas the working stimulus is altered using a *handedness* and *angle* transformation. To help their decision, participants can offload their mental rotation process onto a physical knob as depicted in (a) that affords rotating the working stimulus on screen. During each trial, the base stimulus is presented in the right half and the working stimulus in the left half of the screen for 5 s or until a response was given (b). The figure is adapted from Weis and Wiese (2019) and depicts 1 out of 24 base stimuli used in this study.

(speed, accuracy). In the opposite handedness condition, the working stimulus was first mirrored with respect to a vertical axis before the angle transformation took place (Fig. 1b). Note that the 0° condition is used as a baseline condition since the external resource only affords rotation, a cognitive process not necessary to solve problems in the 0° condition. The performance goal condition indicated whether participants were motivated to focus on speed or accuracy, respectively. In the accuracy goal condition, trial-based feedback was given with respect to accuracy only (correct/incorrect). In the speed goal condition, feedback was given with respect to speed for correct answers and with respect to accuracy for incorrect answers (speedy/slow/incorrect; compare Fig. 1b). Accuracy feedback for incorrect answers had to be given in the speed condition as well to avoid complete negligence of accuracy and thus omitting performing the cognitive task at hand and instead only responding as quickly as possible. Speed feedback was based on a sliding window consisting of the reaction times of the preceding 32 trials. For responses given faster than the 85th percentile of those 32 trials participants received "Speedy," and for responses given slower than the 85th percentile participants received "Slow" as feedback. Participants were also able to collect goal-specific points throughout the experiment. The best scoring participants were eligible for a monetary reward (for details, see Data S1).

Each participant had to complete 576 trials: three repetitions for each of the 24 stimuli in each of the four angle and two handedness conditions. Trials were presented in three blocks, each consisting of 192 non-identical trials. Within blocks, trials were randomized. Every 16 trials, participants were allowed to take a self-paced break. At the end of each block, participants were reminded that "it is not the best way to always rely on the mind's eye or to always rely on the rotation knob. Try to use each way when it works best." Participants practiced the task for 32 trials with stimuli that were not used in the main experiment. To get a crude idea of how tiring the extended rotation task is, participants were to fill out the Stanford Sleepiness Scale (Hoddes, Zarcone, Smythe, Phillips, & Dement, 1973) before and after the task. The Extended Rotation Task took between 40 and 60 min to complete.

2.1.3. Analysis

To determine whether participants offloaded the mental rotation process onto the knob, a binary variable was created on a trial-by-trial basis that indicated whether the stimulus on the screen was rotated for more than 5° (i.e., offloading) or less than 5° (i.e., no offloading). The threshold of 5° was chosen because it allows simultaneous minimizing of (a) false alarms due to motor jitter and (b) false positives because a rotation of less than 5° is unlikely to help cognitive processing even in the lowest 60° angle condition. To analyze the offloading data, a random coefficient modeling approach that allowed to fit generalized linear models with a logit link function and two random effects, participants and stimuli, was used (for more details on this approach, see Data S1). Models were implemented using R (R Core Team, 2013) and the lme4 package's function glmer (Bates, Mächler, Bolker, & Walker, 2015). Marginal means were computed using the emmeans[5] package.[6]

2.2. Results and discussion

Unsurprisingly, both angle and handedness affected offloading ($|Z| = 13.1$ and $|Z| = 12.4$, respectively; for estimated marginal means, see Fig. 2). More interestingly, changing the performance goal from accuracy to speed, when holding all other predictors constant, was associated with a 83% decrease in offloading odds ($\text{odds}_{\text{accuracy}} = 22.6$, $\text{odds}_{\text{speed}} = 4.0$; $|Z| = 4.9$) or, equivalently, a drop of 16 percentage points in offloading probability ($p_{\text{accuracy}} = .96$, $p_{\text{speed}} = .80$, see Fig. 2). Similarly, but of less importance for the current purposes, changing the performance goal also changed the relationship between angle and offloading ($|Z| = 6.3$) as well as between handedness and offloading ($|Z| = 6.1$); for details concerning these interactions and other model results, see Table S2. To avoid redundancy, accuracy and RT data are reported with Experiment 2A and 2B (see Figs. 3–6; data from Experiment 1 is labeled "free choice" since participants were able to freely choose between internal and external processing in Experiment 1). Increases in reported sleepiness from before to after the rotation task were comparable for both accuracy and speed goal conditions (independent t test: $\Delta(\text{after} - \text{before})_{\text{speed}} = 1.00$, $\Delta(\text{after} - \text{before})_{\text{accuracy}} = 0.91$, $t(84) = 0.31$, $p = .76$). Reported difficulty of the extended rotation task was also comparable across goal conditions (independent t test: $M_{\text{spd}} = 2.78$, $M_{\text{acc}} = 2.55$, $t(84) = 0.31$, $p = .76$; scale ranged from 1 to 5).[7]

In line with *H1*, problem solvers altered their cognitive offloading behavior based on their performance goals[8] while the available internal and external resources were kept constant. Participants almost exclusively rotated externally when aiming for accuracy and relied more on mental rotation when aiming for speed. Note that participants had a pronounced preference for external rotation for both conditions. Possible reasons include minimization of mental effort (Ballard, Hayhoe, Pook, & Rao, 1997), a generally more favorable performance profile of the external strategy, or a large proportion of participants who use internal and external strategies in parallel. Also note that we do not suggest accuracy goals to be always specifically associated with increased offloading. Instead, we conclude performance goals to have substantial impact on the way problem solvers mix internal and external strategies in general.

3. Experiment 2: Forced choice

The confirmation of *H1* laid the foundation for Experiment 2 in which we investigated whether the differences in offloading behavior exhibited in Experiment 1 were associated with goal-related performance gains. We asked one group of participants to solve the extended rotation task while exclusively relying on their internal resources without availability of an external resource (forced internal *cognition locus* condition) and another group of participants to exclusively rely on the external resource (forced external *cognition locus*).[9] We then compared performances in these forced conditions to performance in the setting of Experiment 1 (free choice *cognition locus*). This way of comparing forced and free strategy choices has been termed the Choice/No-Choice Method (Siegler & Lemaire, 1997).

Specifically, we expect the offloading behavior exhibited in Experiment 1 to be associated with high goal-related performance. We expect that participants in the free choice

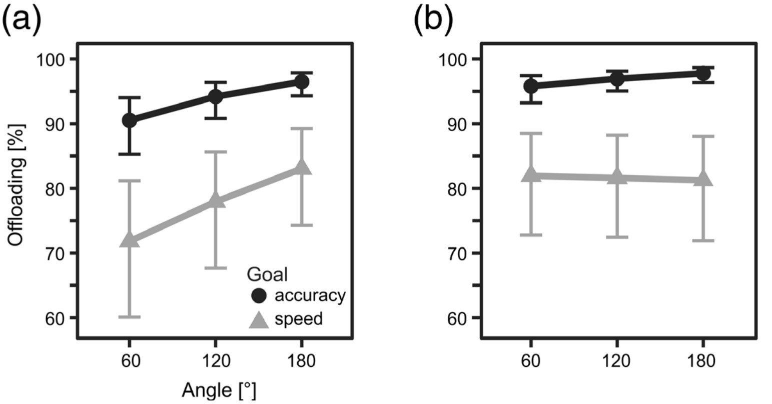

Fig. 2. Model-based offloading proportions for different (a) and same (b) handedness. Error bars depict asymmetric 95% CIs that have been back-transformed from the logit scale.

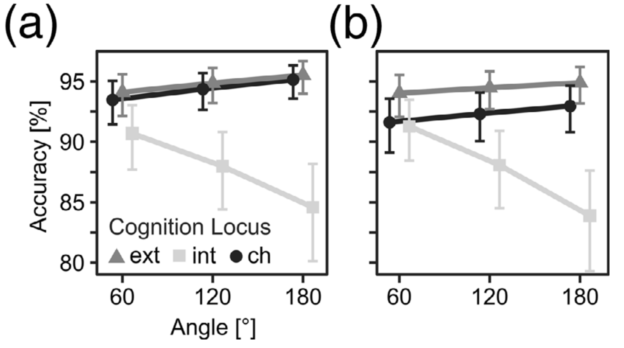

Fig. 3. Model-based correct answer probabilities for different (a) and same (b) handedness in Experiment 2A. Error bars depict asymmetric 95% CIs that have been back-transformed from the logit scale. ext: forced external, int: forced internal, ch: free choice.

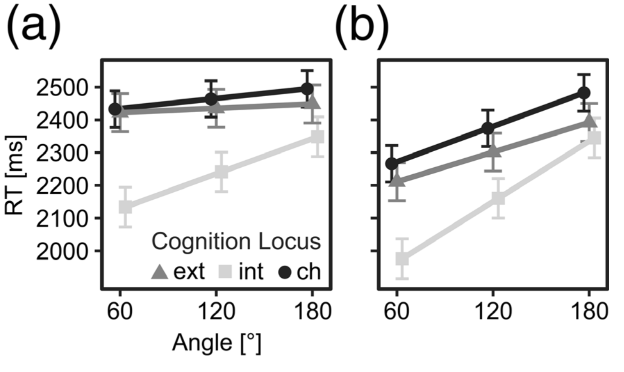

Fig. 4. Model-based reaction time estimates for different (a) and same (b) handedness in Experiment 2A. Error bars depict 95% CIs. ext: forced external, int: forced internal, ch: free choice.

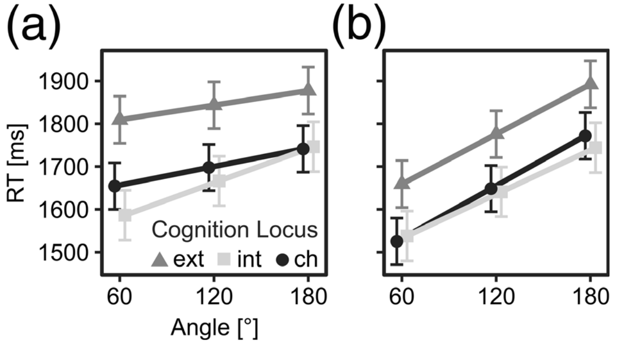

Fig. 5. Model-based reaction time estimates for different (a) and same (b) handedness in Experiment 2B. Error bars depict 95% CIs. ext: forced external, int: forced internal, ch: free choice.

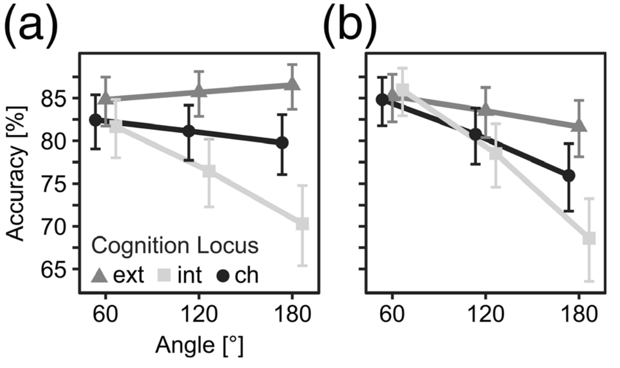

Fig. 6. Model-based accuracy estimates for different (a) and same (b) handedness in Experiment 2B. Error bars depict asymmetric 95% CIs that have been back-transformed from the logit scale. ext: forced external, int: forced internal, ch: free choice.

condition (Experiment 1) should be at least as accurate as the more accurate of the two forced groups in the accuracy goal condition (Experiment 2A) and at least as fast as the faster of the two forced groups in the speed goal condition (Experiment 2B); *H2-1*. Additionally, we explore the possibility that participants in the free choice condition (Experiment 1) sacrificed performance in the metric not relevant to the current goal (i.e., sacrificed accuracy in the speed goal and speed in the accuracy goal condition); *H2-2*.

3.1. Methods and materials

More information on methods and materials, including information about participants, apparatus, stimuli, procedure, and data filtering can be accessed in Data S1. The final sample consisted of 77 students (41 forced external, 36 forced internal) in Experiment 2A and of 75 students (40 forced external, 35 forced internal) in Experiment 2B. Data and R analysis script are available through the Open Science Framework at https://osf.io/sh6qa/.

3.1.1. Design changes

Task and design were identical to Experiment 1 except that participants were not able to freely choose whether or not to recruit the external resource (factor *cognition locus*). Two experiments were conducted: Participants were asked to be as accurate (i.e., the accuracy *performance goal* of Experiment 1) in Experiment 2A and to be as fast (i.e., the speed *performance goal* of Experiment 1) as possible in Experiment 2B.

3.1.2. Analysis

Accuracy *performance goal* data from Experiment 1 was added to the analysis of Experiment 2A and speed *performance goal* data from Experiment 1 to the analysis of Experiment 2B and labeled "free choice." The same data-analytic approach as in Experiment 1 has been employed. Note that Experiment 2 was conducted after Experiment 1 and participants were thus not randomly assigned to one of the three performance goal conditions, thereby introducing a possible confound (i.e., time point of data collection).

3.2. Experiment 2A: Results and discussion (forced choice, accuracy goal)

3.2.1. Accuracy

In comparison to participants in the forced internal *cognitive locus* condition, when holding all other predictors constant, the odds of solving a problem correctly was increased by 116% for participants in the forced external and free choice conditions combined ($|Z| = 5.2$; $\text{odds}_{\text{choice}} = 14.2$, $\text{odds}_{\text{forced external}} = 17.8$, $\text{odds}_{\text{forced internal}} = 7.3$). Equivalently, when transforming the odds back to probability values, participants in the forced internal condition were about five percentage points less accurate than participants in the forced external and choice conditions ($p_{\text{choice}} = .95$, $p_{\text{forced external}} = .96$, $p_{\text{forced internal}} = .91$; p refers to the probability of answering accurately; Fig. 3). Accuracies between forced external and choice conditions did not differ ($|Z| = 1.39$). The remaining model results are reported in Table S4. Increases in reported sleepiness ($\Delta(\text{after} - \text{before})_{\text{ext}} = 1.35$, $\Delta(\text{after} - \text{before})_{\text{int}} = 1.03$, $t(74) = 1.14$, $p = .26$) and reported difficulty of the extended rotation task ($M_{\text{ext}} = 2.50$, $M_{\text{int}} = 2.53$, $t(74) = -0.12$, $p = .90$; scale ranged from 1 to 5) were comparable for both forced cognition locus conditions.[10]

In sum, accuracies in the free choice and forced external conditions were comparable while accuracy in the forced internal condition was considerably lower. Thus, participants in the choice condition employed a combination of internal and external resources that afforded high goal-related performance, suggesting an adaptive use of the external resource (confirming *H2-1*).

3.2.2. Speed

Analyzing RT in addition to accuracy data allows the exploration of whether participants in the choice condition sacrificed speed to achieve high accuracy. Such behavior would speak for our participants' ability to choose cognitive strategies in a way that specifically maximizes goal-related rather than generic performance.

Results show that participants did indeed sacrifice speed to maximize accuracy: RTs in the forced external and free choice conditions were similar ($\Delta RT = 51$ ms, $|t| = 0.8$)[11] whereas participants in the forced internal condition answered considerably faster than participants in the external and choice conditions combined ($\Delta RT = 193$ ms, $|t| = 3.4$). Results are also in accordance with the classical finding by Shepard and Metzler (1971) that reaction time increases linearly with angle ($|t| = 27.5$),[12] which can be seen as a manipulation validation. The remaining model results are reported in Table S6 and illustrated in Fig. 4. To further illuminate the choice process, we analyzed the onset of external processing: in the free choice condition, participants started using the knob more than 200 ms later than in the forced external condition (Table S7, Fig. S4); this suggests either a sequential processing approach or a costly choice process and is discussed in section 7.6 of Data S1. It also suggests that participants in the forced external condition followed instructions as they did not exhibit the internal, roughly 200 ms-lasting, processing participants in the choice condition engaged in.

In sum, RTs in the free choice and forced external conditions were comparable whereas RT in the forced internal condition was considerably lower. Thus, problem solvers in the choice condition have employed a combination of internal and external resources that sacrificed goal-irrelevant performance (confirming *H2-2*). The result also shows that a problem solver's inclination to optimize for speed (Gray et al., 2006; see also Weis & Wiese, 2018) can be superseded by conflicting goals.

3.3. Experiment 2B: Results and discussion (forced choice, speed goal)

One might argue that the extensive offloading of 96% in the free choice accuracy goal condition (Fig. 2) was only accidentally related to benefits in goal-related performance while the true underlying motivation was different (e.g., minimizing mental effort; Ballard et al., 1997; Kool, McGuire, Rosen, & Botvinick, 2010; or because incremental feedback on the display when offloading is preferred over no feedback when not offloading; Fu & Gray, 2004). The purpose of Experiment 2B is to confirm the results of Experiment 2A by investigating whether participants that could freely choose in the speed *performance goal* condition of Experiment 1 exhibited high goal-related performance despite considerably less offloading (i.e., 80% instead of 96%).

3.3.1. Speed

Participants were equally fast in the forced internal and the free choice conditions (ΔRT = 19 ms, $|t| = 0.3$), whereas participants in the forced external condition were responding considerably slower than participants in the other two conditions combined (ΔRT = 146 ms, $|t| = 2.4$); Fig. 5. The remaining model results are reported in Table S9. Participants in forced internal condition reported higher increases in sleepiness ($\Delta(\text{after} - \text{before})_{\text{int}} = 1.35$, $\Delta(\text{after} - \text{before})_{\text{ext}} = 0.78$, $t(72) = -2.14$, $p = .04$)[13] and higher difficulty of the extended rotation task ($M_{\text{ext}} = 2.37$, $M_{\text{int}} = 3.18$, $t(73) = 3.00$, $p = .004$; scale ranged from 1 to 5) than participants in the forced external cognition locus condition. As in Experiment 2A, we also analyzed the onset of external processing: in contrast to Experiment 2A, participants in the free choice condition started using the knob equally fast as in the forced external condition (Table S14, Fig. S8); this suggests a non-sequential processing approach and is discussed in in section 8.6 of Data S1.

In sum, RTs in the free choice and forced internal conditions clustered together and were considerably lower than RT in the forced external condition (which further confirms *H2-1*). Interestingly, the exploratory analyses of sleepiness and difficulty of the extended rotation task both suggest internal resource use to be more taxing than external resource use. Note that such a difference could only be shown for the speed goal, not for the accuracy goal condition and that participants were, when given the choice, less likely to offload when speed instead of accuracy was incentivized. This suggests that participants did not offload cognition merely to minimize effort but instead offloaded cognition to meet their performance goals. Lastly, also note that participants were nearly 150 ms slower when solving the task externally 100% of the time (forced external) in comparison to solving it externally 0% of the time (forced internal) but also in comparison to solving it externally 80% of the time (free choice). This pattern suggests that adaptively switching strategies in the minority of only 20% of trials made up for the majority of the RT difference, which could have possibly been realized by monitoring strategy performance in a stimulus (i.e., feature-specific) way (as proposed in the ASCM; e.g. Siegler & Lemaire, 1997). This possibility is backed by a supplemental analysis that shows that participants were about 265 ms faster when solving problems internally in the free choice in comparison to the forced internal condition (Tables S10 and S11; Fig. S6).

3.3.2. Accuracy

In comparison to participants in the forced external condition, when holding all other predictors constant, the odds of solving a problem correctly was decreased by 31% for participants in the forced internal and free choice conditions combined ($|Z| = 3.8$; $\text{odds}_{\text{choice}} = 4.3$, $\text{odds}_{\text{forced external}} = 5.5$, $\text{odds}_{\text{forced internal}} = 7.3$;). Equivalently,[14] participants in the forced external condition were about five percentage points more accurate than participants in the forced external and free choice conditions combined ($p_{\text{choice}} = .81$, $p_{\text{forced external}} = .85$, $p_{\text{forced internal}} = .78$). Accuracy for the forced internal and the free choice condition did not differ ($|Z| = 1.9$). Remaining model results are reported in Table S13 and illustrated in Fig. 6.

These results again suggest that problem solvers in the free choice condition employed a combination of internal and external resources that sacrificed goal-irrelevant performance (further conforming *H2-2*). Cognition locus main effects of all experiments combined are summarized in Fig. 7.

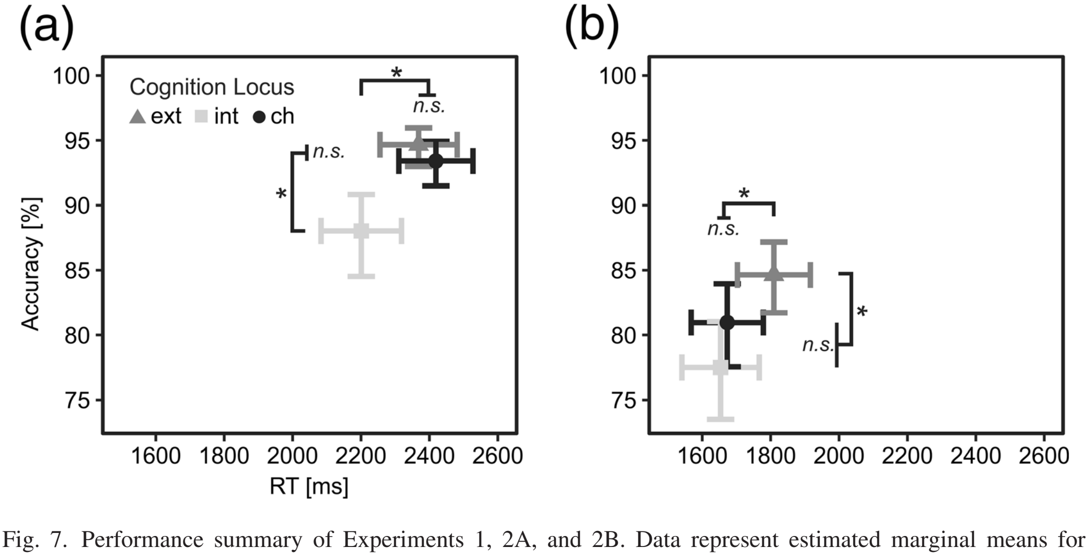

Fig. 7. Performance summary of Experiments 1, 2A, and 2B. Data represent estimated marginal means for the accuracy (a) and speed (b) goal conditions. ext: forced external, int: forced internal, ch: free choice, *: $|t|$ or $|Z| \geq 2$; n.s.: $|t|$ or $|Z| < 2$.

4. General discussion

We asked participants to solve a cognitive task, provided them with different performance goals—maximizing speed or accuracy, respectively—and measured how frequently (Experiment 1) and how proficiently (Experiment 2) they made use of a novel external resource to support their cognitive processing. Results showed that participants with different performance goals indeed exhibited differential offloading frequencies (*H1*), which reflected the participants' proficiency in distributing cognition between internal and external resources in a goal-directed manner. In particular, the way participants mixed internal and external resources led to high goal-related performance (*H2-1*), whereas goal-unrelated performance was sacrificed *(H2-2)*. In other words, participants were specifically concerned with goal-related rather than generic performance.

4.1. How much guidance do problem solvers need to choose between internal and external resources to meet their cognitive goals?

The study's main purpose was to find out whether humans possess the ability to autonomously exploit their technologized environments in pursuit of their cognitive goals. The promising main takeaway is that participants were performing very well without any external guidance in the current extended rotation paradigm. This suggests the human to be capable of proficiently navigating a world with a steadily increasing number of possibilities to offload cognition. Humans can thus not only reach high levels of *generic* performance when mixing internal and external strategies (Gilbert, 2015; Gray et al., 2006; Risko & Dunn, 2015; Walsh & Anderson, 2009) but they can also reach high levels of *goal-related* performance (current study). Clear performance goals and a steady feedback might be all that is needed for deciding on how to mix internal and external resources. The present results are in line with the notion of the human as an independent and rational problem solver (cf. Anderson, 1990).

However, one should be aware that the present finding of good goal-related performance without guidance might not generalize to all possible external resources and environments. For some situations, it is already known that guidance is beneficial, for instance when a problem solver once read faulty information about an external resource's performance. In such a situation, the problem solver would likely include that faulty information in his or her decision whether to use that resource (Weis & Wiese, 2019), leading to poor performance. To alleviate the consequences of false beliefs, verbal advice concerning the preferable strategy, given immediately before solving a problem, was shown to improve offloading performance (Gilbert et al.,). In addition to faulty beliefs, one should also consider the impact of the complexity of an environment on the problem solver's ability to proficiently recruit external resources. In complex environments, it can be hard to gauge the utility of a strategy because the associated reward might not be immediate or obvious, or because a wide variety of strategies could be employed and too much effort would be needed to obtain solid estimates of each strategy's utility (cf. Lieder & Griffiths, 2017). In a similar vein, it should be noted the cognitive environment available in the present study afforded only one obvious external strategy (i.e., knob-based rotation) and that challenges in other cognitive environments might include discovery of unknown or creation of novel external strategies (as, for example, in the cognitive environment of the computer game TETRIS®; Kirsh & Maglio, 1994). Lastly, it is uncertain whether performance feedback played an important role for establishing the adaptive offloading behavior. Thus, so far, one can conclude that in the absence of faulty beliefs and complex environments, a condition that was likely met in this study, and the presence of performance feedback, humans are able to employ a well-performing and goal-directed mix of internal and external cognitive strategies without further guidance.

4.2. How do problem solvers establish a goal-driven recruitment of external resources?

To the authors, it is intriguing how the participants realized the goal-driven incorporation of the external strategy into their cognitive processing. Two possible underlying mechanisms exist. First, participants might have focused on the goal-related feedback, that is, used the feedback as an error signal to improve subsequent behavior (i.e., *performance monitoring*; for a review, see Ullsperger, Fischer, Nigbur, & Endrass, 2014). For example, other research suggests that older adults can use accuracy feedback to overcome a bias against using their internal memory (Touron & Hertzog, 2014). Similarly, participants might have monitored their errors and timing independently from the displayed feedback. Second, participants might have made correct metacognitive judgments about the capabilities of the available cognitive resources (for a review, see Risko & Gilbert, 2016). In other words, participants might have metacognitively evaluated the different strategies a priori and opted for the more promising one. Such metacognitive judgments are likely employed (Dunn & Risko, 2016; Weis & Wiese, 2019) but not without fault (Gilbert et al., ; Risko & Dunn, 2015).[15] A third possibility would be that participants chose the path of least effort (Kool et al., 2010) and ended up with good choice performance more or less by chance, which is however a highly unlikely possibility in the current study (for more details, see Section 3.3.1).

From the present data, we cannot distinguish the contributions of performance monitoring and metacognitive evaluations. However, we deem it likely that both mechanisms contributed simultaneously, which has already been proposed for situations in which problem solvers can select between internal and external strategies (Gilbert, 2015; Risko & Gilbert, 2016) and in which they can select between different internal strategies (for a review, see Lieder & Griffiths, 2017). Further studies that capture participants' a priori metacognitive evaluations of different strategies and that track strategy selection and associated performance over time could illuminate the importance of both performance monitoring and metacognitive evaluation for goal-oriented strategy selection. Lastly, it is important to realize that a proficient problem solver is not only able to adaptively choose between given external strategies but is also able to create and use novel strategies in a highly adaptive way (Kirsh, 2013), a topic that is out of the scope of the current article.

4.3. Conclusion and outlook

The current findings support the notion of humans as canny offloaders who are able to employ environment-based strategies to pursue their cognitive goals. Such proficiency seems important in an increasingly computerized world that affords an abundance of environment-based strategies. Future efforts should be focused on the mechanisms that underlie the choice to offload and on further illuminating the circumstances under which problem solvers need guidance to fulfill their goals.

Notes

1. Bocanegra, Poletiek, Ftitache, and Clark (2019).
2. Please note that those performance profiles are not static. Performance profiles can change with increasing expertise and in many settings. For example, with increasing expertise, novel strategies that interleave internal and external processing can be discovered and used (Maglio & Kirsh, 1996). For a model that incorporates the effectiveness of different strategies over time in a problem-specific way, see Siegler and Lemaire (1997).
3. From a more philosophical perspective, it is currently debated whether epistemic actions directly replace internal cognitive processes (see *parity argument* and *extended mind hypothesis* in Clark & Chalmers, 1998; and *first wave extended mind* in Sutton, 2010) or complement and augment internal cognitive processing (*second wave extended mind*; Sutton, 2010).
4. For example, reordering Scrabble tiles is an epistemic action as it unburdens working memory and thereby supports the cognitive task of finding words, possibly by providing a scaffold to start the word search from (Maglio, Matlock, Raphaely, Chernicky, & Kirsh, 1999).
5. https://CRAN.R-project.org/package=emmeans
6. Note that the angle 0 condition is omitted in the main analyses as it is not relevant for offloading the mental rotation process. Analyses for the angle 0 condition can be found in Data S1; Tables S1, S3, S5, S8, and S12; and Figures S1–S4, S5, and S7.
7. Two participants had to be excluded from the sleepiness and one participant from the difficulty analysis due to missing data.
8. And possibly also based on the respective goal-related feedback; see Section 4.
9. Note that the forced external condition might include internal processing as well because participants might not always adhere to the instructions.
10. One participant had to be excluded from both sleepiness and difficulty analyses due to missing data.
11. $|t|$ refers to the absolute value of the Wald statistic as reported by *R*'s lme4 package (Bates, Mächler, Bolker, & Walker, 2015). Here, the t value can be used to gauge whether RTs between conditions are similar or different. Where binary

interpretation is necessary, we use a |t| > 2 criterion to infer difference rather than similarity.

12. More precisely, a one standard deviation increase in angle was associated with a 73 ms increase in reaction time. Since one standard deviation equals 49° in our experiment, a 1° increase in angle is associated with a 1.5 ms increase in reaction time. Please note that this value refers to the main effect, holding the interaction effects constant.
13. One participant had to be excluded from the sleepiness analysis due to missing data.
14. When transforming the odds back to probability values.
15. Note that such evaluations can be made independently from the actual performance of the respective resource (Gilbert, 2015) but that combined strategies in which participants factor performance feedback into their metacognitive evaluations are also plausible.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article:

Data S1. Apparatus, stimuli, procedure, participants, and data filtering and analyses.

Table S1. Generalized linear mixed model results for offloading in Experiment 1 at angle 0.

Table S2. Generalized linear mixed model results for cognitive offloading in Experiment 1.

Table S3. Generalized linear mixed model results for accuracy in Experiment 2A at angle 0.

Table S4. Generalized linear mixed model results for accuracy in Experiment 2A.

Table S5. General linear mixed model results for reaction time in Experiment 2A at angle 0.

Table S6. General linear mixed model results for reaction time in Experiment 2A.

Table S7. General linear mixed model results for offloading onset in Experiment 2A.

Table S8. General linear mixed model results for reaction time in Experiment 2B at angle 0.

Table S9. General linear mixed model results for reaction time in Experiment 2B.

Table S10. General linear mixed model results for reaction time in Experiment 2B: offloading trials only.

Table S11. General linear mixed model results for reaction time in Experiment 2B: internal trials only.

Table S12. Generalized linear mixed model results for accuracy in Experiment 2B at angle 0.

Table S13. Generalized linear mixed model results for accuracy in Experiment 2B.

Table S14. General linear mixed model results for offloading onset in Experiment 2B.

Fig. S1. Model-based offloading estimates as predicted by handedness and performance goal at angle 0. Error bars depict asymmetric 95% CIs that are back-transformed from the logit scale. Goal: Performance Goal Factor; acc: accuracy, spd: speed

Fig. S2. Model-based accuracy estimates as predicted by handedness and cognition locus at angle 0. Error bars depict asymmetric 95% CIs that are back-transformed from the logit scale. f. external: forced external, f. internal: forced internal.

Fig. S3. Model-based RT estimates as predicted by handedness and cognition locus at angle 0. Error bars depict asymmetric 95% CIs. f. external: forced external, f. internal: forced internal.

Fig. S4. Model-based offloading onset estimates for different (a) and same (b) handedness in Experiment 2A. Error bars depict 95% CIs. ext: forced external, ch: free choice.

Fig. S5. Model-based RT estimates as predicted by handedness and cognition locus at angle 0. Error bars depict 95% CIs. f. external: forced external, f. internal: forced internal.

Fig. S6. Model-based reaction time estimates split by offloading**.** Data represents estimated marginal means for the speed goal conditions split by whether participants did or did not offload during the respective trials. Error bars depict 95% CIs. Note that CIs are asymmetric for accuracy estimates. ext: forced external, int: forced internal, ch: free choice. Error bars depict 95% CIs. ext: forced external, int: forced internal, ch: free choice.

Fig. S7. Model-based accuracy estimates as predicted by handedness and cognition locus at angle 0. Error bars depict asymmetric 95% CIs that are back-transformed from the logit scale. f. external: forced external, f. internal: forced internal.

Fig. S8. Model-based offloading onset estimates for different (a) and same (b) handedness in Experiment 2B. Error bars depict 95% CIs. ext: forced external, ch: free choice.