CellPress

Review

Cognitive Offloading

Evan F. Risko[1,*] and Sam J. Gilbert[2,*]

If you have ever tilted your head to perceive a rotated image, or programmed a smartphone to remind you of an upcoming appointment, you have engaged in cognitive offloading: the use of physical action to alter the information processing requirements of a task so as to reduce cognitive demand. Despite the ubiquity of this type of behavior, it has only recently become the target of systematic investigation in and of itself. We review research from several domains that focuses on two main questions: (i) what mechanisms trigger cognitive offloading, and (ii) what are the cognitive consequences of this behavior? We offer a novel metacognitive framework that integrates results from diverse domains and suggests avenues for future research.

Trends

Physical action is sometimes used to reduce the cognitive demands of a task. This is known as cognitive offloading.

Recent studies have begun to investigate the processes that trigger cognitive offloading, and the cognitive consequences of this behavior.

Propensity to offload cognition is influenced by the internal cognitive demands that would otherwise be necessary.

It is also influenced by metacognitive evaluations of our mental abilities.

These metacognitive evaluations are potentially erroneous, which may lead to suboptimal offloading behavior.

Offloading Cognition

A moment's reflection on our day-to-day cognitive lives reveals the intimate relation between human cognition and manipulation of the body and objects in the physical environment. We tilt our heads while trying to perceive ambiguous images, we gesture while imagining spatial transformations, and we rely on smartphones and search engines to store and retrieve information. In other words, we often think using our bodies and the external world. This ability to flexibly deploy *ad hoc* mixtures of internal and external processes in pursuit of our cognitive goals likely represents a defining feature of what it means to be a successful cognitive agent in a complex environment [1–4]. One crucial function that these mind/body/world interactions afford is **cognitive offloading** (see Glossary)–the use of physical action to alter the information processing requirements of a task so as to reduce cognitive demand (see also computational offloading [5]; epistemic actions [6]). Our unaided mental abilities have well-known limits (e.g., we can only accurately perceive a relatively small region of the visual field [7] and can only hold a limited amount of information active in memory [8]). Offloading cognition helps us to overcome such capacity limitations, minimize computational effort, and achieve cognitive feats that would not otherwise be possible. Consistent with this notion, cognitive offloading has been demonstrated to improve performance across several domains (e.g., perception [9], memory [10], arithmetic [11], counting [12], and spatial reasoning [13]).

The term cognitive offloading has long existed in the conceptual repertoire of cognitive scientists, and the phenomenon it refers to is ancient (e.g., finger-counting and abacuses in numerical cognition, systems of knots or quipus for memory [14]). However, cognitive offloading has rarely been the target of systematic experimental investigation in and of itself. This has now begun to change. This change has been precipitated by an increasing interest among cognitive scientists in ‘wider’ conceptions of cognition (e.g., embodied, embedded, extended, and distributed approaches [2,3,15–20]). In addition, increased interest in cognitive offloading is emerging at a time when the opportunity to offload cognition onto technological prostheses has reached a kind of fever pitch–the potential consequences of which (both bad and good) have not gone unnoticed by the general public (‘Is Google making us stupid?’ [21]). Thus research on cognitive offloading offers both a deeper understanding of the physically distributed nature of human cognition and translational insights into its potential use (and abuse) in our day-to-day lives. We review here recent research investigating cognitive offloading across three different domains, focusing on two fundamental issues: (i) what factors influence the likelihood of individuals

[1]Department of Psychology, University of Waterloo, Waterloo, Canada
[2]Institute of Cognitive Neuroscience, University College London, London, UK

*Correspondence:
efrisko@uwaterloo.ca (E.F. Risko) and
sam.gilbert@ucl.ac.uk (S.J. Gilbert).

 http://dx.doi.org/10.1016/j.tics.2016.07.002

offloading cognition versus relying on internal processes alone, and (ii) what are the cognitive consequences of this behavior?

Thinking with the Body

Cognitive offloading can be roughly subdivided into actions that offload cognitive demands onto-the-body and into-the-world. We turn first to the former. Recent research in cognitive science has focused on how we actively use our bodies in the 'here-and-now' to reduce cognitive demand. For example, we use our eyes to index locations in space [22], we use our fingers, point, or nod our head to mark positions in sequential tasks [12,23], we move our hands to externalize thoughts [11,24,25] and to simulate spatial transformations [13], and we move or shift our body to simplify perceptual computations [9]. In each of these cases an action is spontaneously performed in the context of an ongoing cognitive act so as to generate some form of cognitive savings.

A straightforward example of this type of cognitive offloading is **external normalization**. For instance, when individuals encounter a rotated stimulus (e.g., a tilted book) they often physically tilt their head to normalize its orientation. This behavior is an example of external normalization and can be considered as a means to offload **internal normalization**, which is an internal transformation (in this case mental rotation) that aligns a representation of a stimulus with a representation stored in memory [26,27,82]. Indeed, external normalization can reduce the costs of stimulus rotation [9]. One of the major tasks in understanding cognitive offloading is to determine the factors that influence whether some external means is integrated into the performance of a given cognitive act or not. In the context of external normalization, one of the crucial factors is internal demand. Specifically, individuals are more likely to spontaneously physically rotate as the display becomes more disoriented or as the number of items in the display increases [9]. Crucially, both of these manipulations also increase stimulus-rotation costs (i.e., internal demand; a general description of this methodology is provided in Box 1 and Figure 1A). Thus, as the internal demands associated with stimulus rotation increase, the likelihood of spontaneous external normalization also increases. This general pattern has now been observed across several domains (e.g., external normalization [9], prospective memory [10], short-term memory [28], co-speech gesture [29], and co-thought gesture [13]; representative examples are given in Figure 2).

While the relation between internal demand and cognitive offloading is robust, they are nevertheless dissociable. This was revealed in an investigation of external normalization using arrays of words wherein both the words and the frame (i.e., the overall structure of a multi-element array) were rotated, versus arrays where the words were rotated but presented within an upright frame [30] (Figure 1A). These two conditions yield similar rotation costs and similar responses on a physiological measure of demand [30,31]. Nevertheless, spontaneous rates of external normalization are much higher when both the words and the frame are rotated compared to when only the words are rotated. This dissociation is argued to arise because individuals rely on an erroneous metacognitive evaluation of demand. This evaluation may be led astray by intuitive beliefs regarding the effects of stimulus rotation, or a history of external normalization with displays featuring word and frame rotation. Consistent with this account, individuals incorrectly report that rotated word and frame displays are more time-consuming and error-prone, and judge these displays to be more effortful to read than displays with only the words rotated [30].

Putting Cognition Into-The-World

Like offloading cognition onto-our-body, offloading cognition into-the-world is a ubiquitous part of our everyday cognitive lives [4,14,32,33]. A key way in which we offload cognitive processes into-the-world is by using it as a repository of representational information, thus eliminating the need for an internal representation. For example, individuals might write down [28], type into a computer [34,35], sketch [36], or in some other manner alter the environment so as to record information that needs to be remembered [14,37]. We discuss examples of this below.

Glossary

Cognitive offloading: the use of physical action to alter the information processing requirements of a task so as to reduce cognitive demand.
External normalization: the use of physical action (e.g., head tilt) to align a stimulus with a representation stored in memory.
Feeling-of-knowing: predictions made by an individual about whether they will be able to retrieve specific information.
Intention offloading: creation of a cue in the external environment to trigger a delayed intention.
Internal normalization: use of an internal transformation (i.e., mental rotation) to align an internal representation of a stimulus with a representation stored in memory.
Metacognition: higher-order thinking, or 'thinking about thinking', to enable evaluation and control of one's mental processes.
Stroop task: a reaction-time task involving conflict between two stimulus dimensions (e.g., the color and meaning of word stimuli)
Transactive memory system: a memory system composed of a group that collectively encodes, stores, and retrieves knowledge.

Box 1. Methods: The Choice/No Choice Paradigm

Research on cognitive offloading has relied heavily on variants of the choice/no choice paradigm [84]. The application of the paradigm is straightforward: in some conditions participants are obliged (i.e., they have no choice) to employ a particular strategy and in others they are free (i.e., they have the choice) to select among a set of available strategies. Each condition and the comparison between conditions provides answers to theoretically interesting questions. In addition, these conditions are typically paired with one or more other manipulations that influence some variable of interest (e.g., memory load). Below we provide an illustrative example using offloading memory onto an external medium (e.g., a piece of paper or a computer).

No Choice–Internal

Individuals are tasked with remembering a given piece of information without being able to store it externally. This condition provides a measure of performance when the individual has to rely solely on their internal memory.

No Choice–External

Individuals are tasked with remembering a given piece of information and must store it externally. This condition provides a measure of performance when the individual uses external memory. It is important to note that unlike the 'no choice–internal' condition this condition cannot ensure that the information is not also stored internally. The comparison of the two 'no choice' conditions provides a measure of the relative effectiveness of storing information internally and externally. This comparison is often made as a function of some other variable (e.g., the amount of to-be-remembered information).

Choice

Participants are allowed to freely choose between storing information internally or externally. This condition provides a measure of the spontaneous offloading of memory demands onto the external medium. Again, how the spontaneous offloading of memory demands changes as a function of some other variable (e.g., the amount of to-be-remembered information) is typically of interest. This condition also provides a measure of performance when the individual uses their 'preferred' strategy.

Challenges

The choice/no choice paradigm is not without challenges. As noted above, attempting to oblige individuals to adopt a strategy might not be effective in some circumstances. In addition, forcing individuals to use a particular strategy could introduce demands associated with being required to inhibit the use of another possibly preferred strategy. For example, restricting individuals from gesturing could impose its own load associated with inhibiting naturally occurring gestures [11].

Offloading Memory–Prospective Memory

We rely on memory not only to recall information from the past but also to execute intended behaviors in the future. Our ability to remember delayed intentions is termed 'prospective memory' [38,39]. Everyone is familiar with its fallibility: failures of prospective memory probably comprise a majority of self-reported everyday memory problems [40]. What makes remembering delayed intentions particularly difficult is that, in many cases, our intentions are not effectively triggered by perceptual cues in our environment, and therefore action must be self-initiated. It is therefore unsurprising that people have long supported prospective memory by using external tools to supply perceptual cues that can trigger intended actions. Examples include tying knots in handkerchiefs, placing reminders in the environment (e.g., post-it notes or task-relevant objects), or–in recent times–using smartphones or wearable devices that can provide time-, location-, or person-based reminders [41,42]. This form of cognitive offloading–acting on the environment to create external triggers for delayed intentions–has been referred to as **intention offloading** [10,43]. Laboratory studies of prospective memory have generally considered our tendency to outsource intentions to external tools as a source of noise that obscures 'real' prospective memory processes, and prevented individuals from setting external reminders (e.g., [44]). However, intention offloading is likely central to our ability to remember intentions in the real world, and is hence an important topic for investigation. This process was investigated empirically in a recent series of behavioral [10,43] and neuroimaging [45] studies illustrated in Figure 1B.

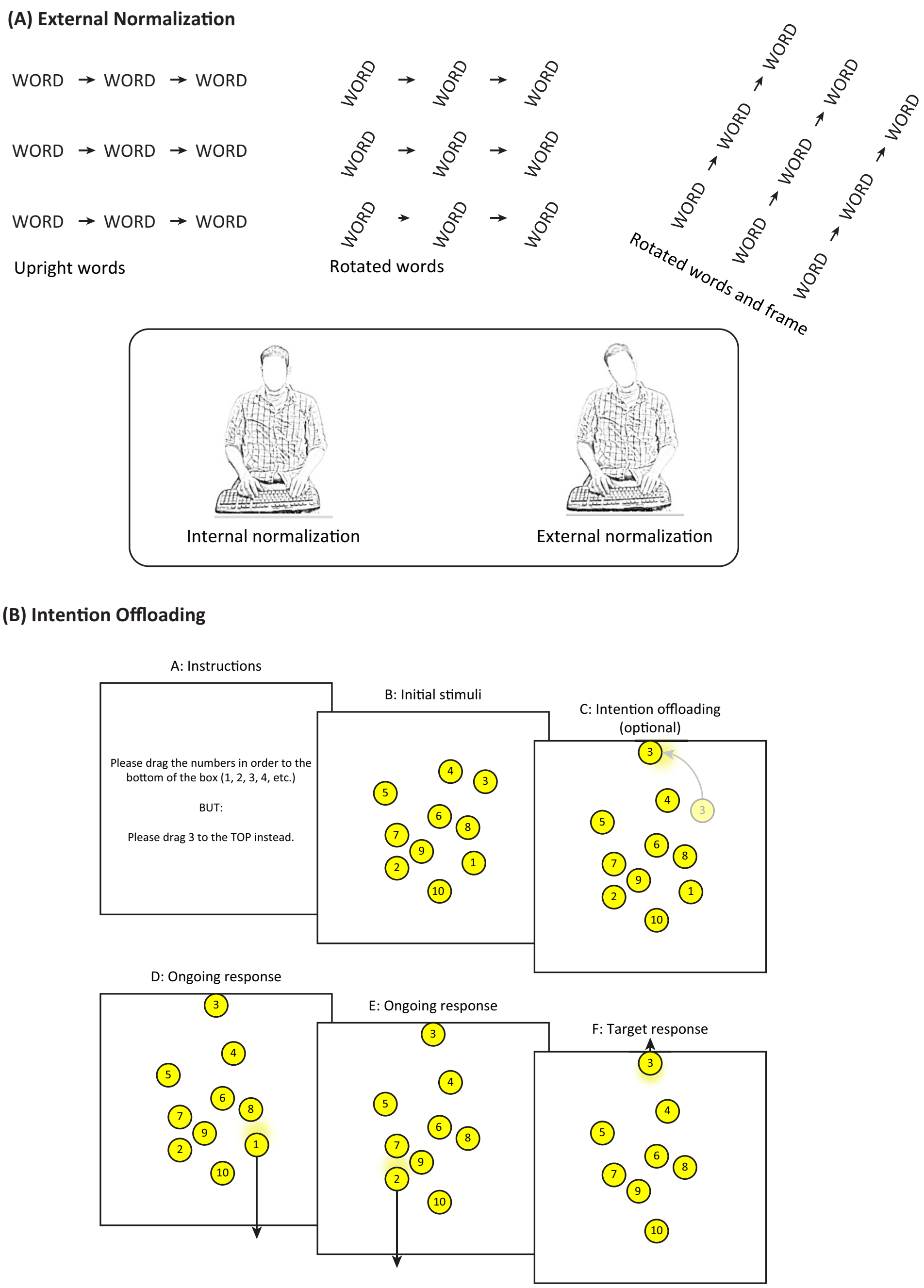


Figure 1. Paradigms for Investigating Cognitive Offloading. (A) In the external normalization paradigm [9] participants read arrays of words that are presented in upright or rotated orientations. When faced with rotated words, participants can align them using internal cognitive processes ('internal normalization') or physical action ('external normalization'). (B) In the intention offloading paradigm [10] participants use a mouse or touchscreen to drag numbered circles in sequence to the bottom of the screen. They are also instructed at the beginning of the trial that one or more of these circles should be dragged to an alternative location. They can either remember these intentions internally or offload them by dragging target circles toward their intended location at the beginning of the trial. In some ways this is analogous to everyday offloading behavior such as leaving an item by the front door so that we will remember it when leaving the house. For a demonstration of the task, please visit 'http://samgilbert.net/offloadDemo.html'. Illustrations modified, with permission, from [9] and [45].

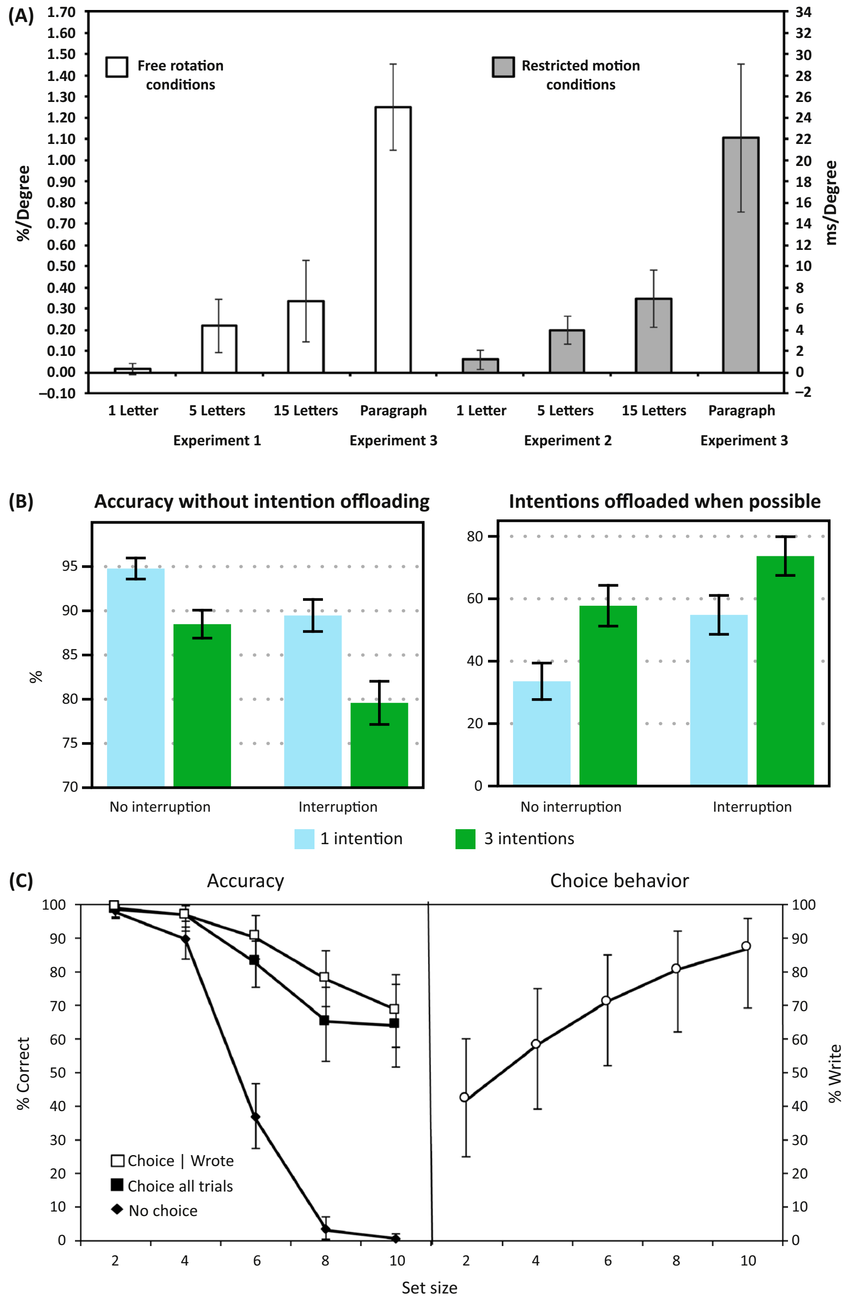


Figure 2. Relation between Internal Demand and Cognitive Offloading. There exists a consistent relation between the amount of internal demand, as indexed in a condition where offloading is restricted, and the amount of spontaneous offloading behavior observed in a condition where the behavior is not restricted. This has been demonstrated across several different domains. With respect to external normalization (A), as the internal costs of stimulus rotation increase when individuals are forced to remain upright (i.e., see rotation costs in ms/degree in 'Restricted motion conditions'; larger values represent greater costs), the likelihood that an individual spontaneously physical rotates increases (i.e., see 'Free rotation conditions'; larger values represent a higher frequency of offloading [9]). In intention offloading (B) and short-term memory (C), as the unaided memory performance decreases (see 'Accuracy without intention offloading' in B and 'Accuracy: no choice' in C), the likelihood that an individual spontaneously offloads the memory demands into the environment (i.e., setting reminders; writing the to-be-remembered items down) increases (see 'Intentions offloaded when possible' in B and 'Choice behavior' in C; in both cases higher values represent a higher frequency of offloading [10,28]). Graphs modified, with permission, from [9], [28], and [43].

Box 2. Perspectives on Cognitive Impartiality

In discussions about cognitive offloading a central question arises with respect to whether the cognitive system has an inherent bias away from specific types of effort. For example, in selecting between storing information in short-term memory (i.e., in-the-head) or writing that information down (i.e., in-the-world [28]) individuals are selecting the type of effort that will be required to carry out the task–more internal or cognitive effort in the former case, and external or perceptual/motor effort in the latter case. Two views have dominated discussions of this issue ([2] for further discussion). On the cognitive impartiality view the cognitive system has no bias or is indifferent to the type of effort required. For example, according the soft constraints hypothesis [85,86], it is not the type of effort but rather the amount of time required that determines the preferred solution (i.e., the solution with the shorter time being the preferred one). An alternative view, which might be called the 'cognitive miser' view, is that individuals have an inherent bias against expending cognitive effort. There has been much recent work on the tendency of individuals to avoid this type of effort [87,88]. One influential theoretical position that embodies this view is the 'minimal memory' view [22], according to which the cognitive system is biased toward minimizing demands on memory (even in the face of potentially greater perceptual-motor costs). Between these theoretical signposts likely lie several interesting alternatives; for example, individuals may have idiosyncratic biases in one direction or the other, or variable task-dependent biases. Future work aimed at adjudicating between these and related views will provide deeper understanding of the how the cognitive system distributes resources across brain, body, and world.

Similarly to tilting one's head to read rotated text, intention offloading is influenced by the internal demands that would otherwise be necessary (Figure 2). Individuals are more likely to offload intentions when their memory load increases or when they encounter interruptions; both these factors impair performance when offloading is prevented [10]. However, and again analogously to external normalization, intention offloading is not only driven by objective need but also by a potentially erroneous metacognitive evaluation of demand. This was demonstrated in a study where individuals remembered delayed intentions both with and without the ability to set reminders, and also provided predictions about their performance. Individuals with lower confidence in their memory abilities were more likely to spontaneously set reminders, even after controlling for any influence of objective ability (which also predicted intention offloading [43]). Interestingly, this relation with metacognitive confidence is domain-general. When individuals performed a separate perceptual judgment task where accuracy was held constant with a staircase procedure, individuals with lower confidence in their perceptual judgments set more reminders in the intention offloading task [43]. Thus, intention offloading is related not only to individual differences in objective ability but also to domain-specific and domain-general metacognitive confidence.

Once an individual has opted to offload, what are the consequences for information processing? In the context of intention offloading, placing information into the external environment brings several potential benefits. One of the most salient is that offloaded representations may be more durable and less prone to distortion than those stored internally, leading to an increased likelihood of intention fulfillment [10,43]. However, it is important to note that individuals also set reminders in conditions where doing so led to no objective increase in accuracy [10,43]. This also occurs in the context of external normalization [9]. This tendency to engage in offloading despite it not benefiting performance may result from (i) an undetected performance benefit (ii) a bias against cognitive effort (Box 2), and/or (iii) an erroneous metacognitive belief that the offloading will in fact benefit performance. Support for the latter interpretation comes from recent research examining offloading in a short-term memory task [28]. Participants were allowed to offload to-be-remembered materials (i.e., by writing them down) and did so about 40% of the time when they were required to remember only two items, a memory load at which performance was already at ceiling without offloading. Crucially, individuals erroneously judged that offloading would improve their performance in this latter condition. Thus, the putatively superfluous offloading (observed across several domains) underlines again the importance of metacognitive beliefs in cognitive offloading.

Offloading Memory–Transactive memory

While the research reviewed thus far has focused little on the cognitive consequences of offloading, recent research on transactive memory has made this issue its primary focus. In **transactive memory systems**, knowledge is distributed across two or more individuals such that the system as a whole knows more than any one individual [46–48]. Recent research has extended this notion of socially distributed memory to human-technology transactive memory systems [34,49–52]. Our ability to reliably store and (almost) instantaneously retrieve information has changed drastically with the advent of the computer and the internet. Consequently we can now offload much of what in the past would have been stored internally.

To examine the idea that offloading might impair our memory, in one study individuals were presented with a series of trivia statements to remember and were asked to type them into a computer. In addition, half the individuals expected that the information would be saved and half expected it to be erased [34]. Recall tests demonstrated that those in the latter condition had better memory than the former. The authors argued that memory-encoding demands were offloaded onto the external store, leading to memory impairments when it was not available ([34]; see Box 3 for additional costs of cognitive offloading). Interestingly, these offloading-based memory impairments can be accompanied by enhanced memory for other information. For example, when individuals saved an initial list of words it enhanced memory for a second list [35]. The authors argued that saving reduced the likelihood that the first list of words interfered with memory for the second (i.e., reduced proactive interference; see also [53]).

Offloading memory demands in a transactive system is not a 'free pass' in terms of mnemonic requirements. Instead, a defining attribute of a transactive memory system is a shift from remembering 'what' to remembering 'where'. For example, when you offload information about a meeting to a file on your computer, you no longer need to remember the content of the file, but you do need to remember where to find it. Consistent with this idea, saving an external file can lead to an enhanced ability to recall where to find information, at the expense of remembering what it actually is ([34]; for an alternative explanation see [53]). Similarly, when faced with a failure to recall memory content, thoughts about memory location can be primed relatively automatically. This was demonstrated in a study where individuals answered easy or difficult trivia questions, then completed a variant of the **Stroop task** [34]. Stroop-like interference from words relating to internet search engines was increased after individuals answered difficult compared with easy questions, consistent with those terms being primed in individuals' minds.

Beyond its influence on memory, being part of a human-technology transactive memory system can also have subtle effects on **metacognition**. For example, searching for information online about one topic can lead individuals to believe that they have more knowledge 'in-the-head' and generate more 'brain activity' when answering questions about another topic [49]. In a separate line of experiments, individuals who had recently used Google to help them complete a quiz reported higher levels of cognitive self-esteem. They also predicted that they would do better on a subsequent quiz, even without help from external resources [50,51]. These results suggest that participating in a human–internet transactive memory system can lead individuals to blur the distinction between what they know and what the internet 'knows.' However, this outcome does not occur in all circumstances. In another study, participants had to report whether they knew the answer to a general knowledge question or not. In one condition, if participants responded that they did not know the answer, they looked it up on the internet. In a second condition, if participants responded that they did not know the answer, they simply moved on to the next question. Thus, participants had access to the internet in one condition and no access in the other. Crucially, when they knew they would subsequently have access to the internet, participants were more likely to answer 'don't know' and reported lower **feeling-of-knowing** to the trivia questions [52]. Thus, internet access in this context reduced individuals' willingness to offer

Box 3. Beyond Google: The Costs of Offloading

GPS

Many people now travel using global positioning systems. Offloading wayfinding onto such a device has been demonstrated to impair spatial memory [65–67]. For example, in one study individuals who drove a predetermined route using a turn-by-turn navigation system outperformed individuals who had no aid. However, individuals in the former group had poorer memory for scenes from the route and, when asked to drive the route a second time without an aid, performed more poorly [67].

Cameras

In an examination of the influence of taking a picture on memory, individuals visited several objects and either took a picture or simply observed the object [89]. Memory for the objects tested a day later revealed impaired memory for the photographed objects. In a subsequent experiment, taking a picture of only part of the object, rather than the whole object, to some extent ameliorated this cost [89]. It was argued that the act of taking a photograph led individuals to offload the memory for the object onto the camera [89]. The impairment observed here is particularly interesting because individuals did not necessarily expect to have the pictures available during the memory test. Thus, the de-prioritization of information that is potentially available externally might occur spontaneously [90].

Automation

In many cases the decision to offload is not made by the individual. Instead, offloading is 'built-in' to the task environment by design. This could reflect a desire to increase usability [91,92] or automate tasks entirely [93–95]. With respect to offloading associated with automation, research has focused on two costs that have been observed across several safety-critical situations (e.g., aviation, medicine, driving), specifically 'automation complacency', the failure to be sufficiently vigilant with respect to the performance of automated processes; and 'automation bias', the tendency to uncritically rely on the output of an automated decision aid [93]. The long-term reliance on automated processes could also lead to cognitive 'skill decay' where a developed ability deteriorates over time [96–98]. Recent research has highlighted the fact that the consequences of automation on performance can be tied closely to how individuals allocate resources freed up by automation. For example, driving a highly automated vehicle can improve situation awareness relative to manual driving if individuals are motivated to attend to the environment, but can impair it if they decide to devote 'freed resources' to driving-unrelated tasks [99].

an answer to a question based on their own knowledge. Taken together, this research underscores the fact that opportunities to offload cognition can affect both lower-level cognitive systems (e.g., memory) and higher-level metacognitive evaluations of those systems (e.g., confidence).

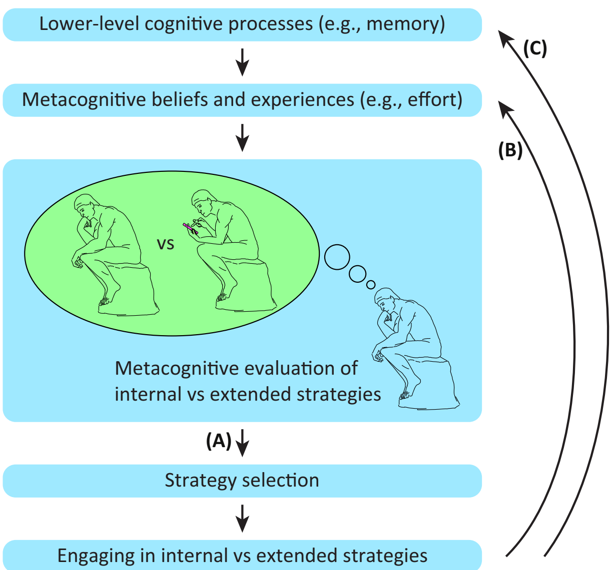
Metacognition of the Extended Mind

The reviewed research suggests that theorizing on cognitive offloading may benefit from further investigation of the metacognitive aspects of both the processes that trigger cognitive offloading and the consequences of this behavior. We offer a framework to support this effort here (Figure 3, Key Figure). This framework describes situations in which there are two or more ways of achieving a goal, one of which involves cognitive offloading and one of which does not. In these circumstances, offloading represents a type of strategy to achieve some cognitive goal, and follows a strategy-selection phase [54–58,83]. This strategy-selection phase is influenced by a metacognitive evaluation of the available options (arrow A in Figure 3). In particular, it is informed by metacognitive beliefs (relating to the person, task, and strategy) and experiences (e.g., effort [30,32,59,60,83]) that are associated with internal and more 'extended' strategies (i.e., those integrating an external body- or physical environment-based resource). For example, when faced with a need to remember a given piece of information, our knowledge regarding our previous success with internal (e.g., metacognitive confidence) and external storage [43,61,62], our beliefs about the reliability of a particular external store [35], and/or a feeling of fluency could all contribute to whether an individual stores that information internally or offloads the memory demands into-the-world. This framework places at center stage a need for a deeper understanding of the metacognitions associated with cognitive offloading, and generates several interesting avenues for future research (see Outstanding Questions).

CellPress

Key Figure

A Metacognitive Model of Cognitive Offloading



Trends in Cognitive Sciences

Figure 3. We propose that selecting between offloading and relying on internal processes is influenced by metacognitive evaluations of our (internal) mental capacities and the capacities of our extended mental systems encompassing body and world (arrow A). An example of this would be evaluating our unaided spatial memory and a GPS system when deciding how to navigate to a friend's house. In addition, engaging in either internal or extended strategies can influence subsequent metacognitive evaluations (arrow B). For instance, after successful use of a GPS system we may come to believe that it is a more reliable guide than our unaided memory. Offloading can also directly impact on our lower-level cognitive processes (arrow C). An example of this would be a reduction in our internal spatial memory for a location after reliance on GPS navigation.

It is important to note that the strategy-selection phase postulated above does not necessarily imply that individuals are aware of making a choice ([63,64] for discussion of this issue). Clearly, there is a range of situations that putatively involve cognitive offloading, some of which involve conscious deliberation and others of which do not. For example, gesture, which is often associated with cognitive offloading, can occur without individuals necessarily being aware of it. By contrast, choosing between navigating based on stored knowledge versus plugging a set of coordinates into a GPS device is likely more strongly associated with a phenomenology of deliberation and choice. Thus, an important question within the proposed framework will be to examine the extent to which different forms of cognitive offloading involve conscious deliberation or not, and how these cases are similar or distinct.

Our framework also attempts to capture the downstream effects of cognitive offloading on how we think. As reviewed above, recent work has demonstrated that the experience of offloading cognition [49–51] and the opportunity to do so [52] can in and of itself alter our thinking about our internal capacities (i.e., our metacognitions; arrow B in Figure 3). For example, offloading information retrieval onto the internet can inflate our estimates of our own knowledge [49–51]. In addition, this work has demonstrated that cognitive offloading can have both costs and benefits with respect to basic cognitive processes (arrow C in Figure 3). For example, offloading to-be-remembered information can both aid and impair retrieval from internal memory stores [34,35]. It should also be noted that, beyond reducing cognitive demand, offloading could also qualitatively change the processes involved in thinking, communicating, and learning, potentially with both positive and negative consequences [13,14].

The metacognitive framework offered here also highlights potential interactions between offloading and the mechanisms that trigger this behavior. For example, deciding whether to rely on a GPS device for the location of a friend's house versus our internal memory will be informed by beliefs in the relative accuracy of each method (a computation that will likely favor the former strategy; arrow A). The tendency to offload wayfinding to the more accurate GPS will likely reduce both our internal spatial memory for that location (arrow C) [65–67] and our metacognitive confidence in it (arrow B), which will in turn increase the likelihood that we choose to rely on the external artefact in the future (arrow A). Thus the model predicts a type of self-reinforcing pattern that will produce a drift away from reliance on internal capabilities when situated in an environment with effective cognitive technologies ([68] for an example of this type of drift in the context of Inuit wayfinding). Understanding the long-term cognitive consequences of this drift represents an important area of future research.

Practical Implications

Research investigating cognitive offloading has clear practical implications–two of which we highlight here. First, individuals with impaired unaided cognitive ability may particularly benefit from cognitive offloading. How can those who would benefit the most be encouraged to do so [69]? The metacognitive model of cognitive offloading put forward in this article suggests that compensatory offloading strategies are most likely to be adopted in individuals with metacognitive awareness of their impairment. This implies potential challenges in populations with metacognitive difficulties, for example in cases of acquired brain injury where there can be a mismatch between an individual's metacognitive evaluation of their abilities–built up over a lifetime–and the post-injury reality [70,71]. Improving metacognitive insight in cases such as these could lead to more-appropriate compensatory offloading [72]

The second general area in which research on cognitive offloading has important practical implications is education [11,24,73,74]. There has long been interest in the potential utility of educational interventions and aids that allow children to offload some of the cognitive demand while learning (e.g., manipulatives [73,74], calculators [75,76]). For example, gesture helps children learn by ‘lightening the load’ [11] and, interestingly, this benefit appears to outstrip that garnered by offloading demands onto external manipulatives [77]. The latter suggests the need to consider whether different forms of offloading might have different educational consequences. Crucially, any benefit of offloading will be contingent on the fact that the demand being offloaded is unnecessary with respect to the learning goal (see [78] for relevant distinctions between necessary/intrinsic/germane load and unnecessary/extraneous load in learning). In addition, it is important that what is ‘saved’ by offloading is redistributed productively rather than being re-allocated to superfluous activities (e.g., intentional mind-wandering [79]; Box 2 presents a similar issue in the case of automating driving).

Concluding Remarks and Future Directions

Cognitive offloading represents one of the quintessential examples of how we use our body and objects in the external world to help us think. As such, understanding this phenomenon provides a window into the distributed nature of human cognition. It is clear from the present review that offloading can take many forms, but that common patterns exist across domains. In particular, the evidence reviewed above shows that internal demand and metacognitive evaluations of demand play a crucial role in offloading. Furthermore, cognitive offloading can have downstream effects on our low-level cognitive capacities and our subsequent metacognitions. We have suggested that an important future direction for this research will be to better understand the metacognitive processes involved in cognitive offloading, and we have offered a framework to guide this effort. Beyond metacognition, there is a clear need to better understand how offloading demands onto various technologies (e.g., computers, internet, GPS) impact on our organic abilities both in the short- and long-term. The latter represents a particularly pressing concern both for researchers and society in general as our lives come to be more cognitively entangled with these technologies. Conducting this

Outstanding Questions

While much work has focused on cognitive offloading's influence on cognition in the short-term, much less has focused on potential long-term effects. How does offloading over an extended period of time impact on our unaided mental abilities (does Google make us stupid)? How will it influence our metacognitive evaluation of our abilities?

Most work investigating cognitive offloading has focused on adults. How do cognitive offloading strategies emerge developmentally, and how do they change across the lifespan?

There are large individual differences in individuals' use of offloading strategies. To what extent are individual differences in decisions to offload cognition domain-specific or domain-general?

Cognitive offloading comes in many forms. Are these different forms of offloading (e.g., writing with pen and paper versus storing a note in a computer, retrieving information from the internet versus a friend) cognitively equivalent?

What neural mechanisms are responsible for triggering cognitive offloading strategies, and what are the neural consequences?

Given the potential costs and benefits of offloading, it may be useful to encourage individuals to offload more or less than they currently do. What interventions can increase or reduce individuals' propensity to engage in cognitive offloading?

Offloading strategies arguably augment our cognitive fitness, thus raising questions about their role in our evolutionary history. For example, what are the evolutionary origins of cognitive offloading?

Do other species engage in cognitive offloading and, if so, how?

Does the cognitive system have an inherent bias toward cognitive versus non-cognitive forms of effort, or is the system ‘cognitively impartial’ (Box 2)?

needed research, however, is not without challenge. For example, investigating cognitive offloading often requires allowing research participants to move their body and manipulate and interact with their environment. Methods in cognitive science, however, have traditionally been designed to restrict this type of natural behavior [80,81]. Thus, understanding cognitive offloading will require an expansion of the cognitive scientist's methodological toolbox. This and other challenges notwithstanding, future research investigating cognitive offloading promises a deeper understanding of one of the defining attributes of human cognition.

Acknowledgments

E.F.R. was supported by funding from the Canada Research Chairs program (056562), the Natural Science and Engineering Research Council (57109), and an Early Researcher award from the Province of Ontario (058402). S.J.G. is supported by a Royal Society University Research Fellowship.

References

1. Barrett, L. (2011) *Beyond the Brain: How Body and Environment Shape Animal and Human Minds,* Princeton University Press
2. Clark, A. (2010) *Supersizing the Mind,* Oxford University Press
3. Pfeifer, R. and Bongard, J. (2006) *How the Body Shapes the Way We Think: A New View of Intelligence,* MIT Press
4. Donald, M. (1991) *Origins of the Modern Mind: Three Stages in the Evolution of Culture and Cognition,* Harvard University Press
5. Scaife, M. and Rogers, Y. (1996) External cognition: how do graphical representations work? *Int. J. Hum-Comput. St.* 45, 185–213
6. Kirsh, D. and Maglio, P. (1994) On distinguishing epistemic from pragmatic action. *Cognitive Sci.* 18, 513–549
7. Simons, D.J. and Levin, D.T. (1997) Change blindness. *Trends Cogn. Sci.* 1, 261–267
8. Cowan, N. (2010) The magical mystery four: how is working memory capacity limited, and why? *Curr. Dir. Psychol. Sci.* 19, 51–57
9. Risko, E.F. *et al.* (2014) Rotating with rotated text: a natural behavior approach to investigating cognitive offloading. *Cognitive Sci.* 38, 537–564
10. Gilbert, S.J. (2015) Strategic use of reminders: influence of both domain-general and task-specific metacognitive confidence, independent of objective memory ability. *Conscious Cogn.* 33, 245–260
11. Goldin-Meadow, S. *et al.* (2001) Explaining math: gesturing lightens the load. *Psychol. Sci.* 12, 516–522
12. Carlson, R.A. *et al.* (2007) What do the hands externalize in simple arithmetic? *J. Exp. Psychol. Learn.* 33, 747
13. Chu, M. and Kita, S. (2011) The nature of gestures' beneficial role in spatial problem solving. *J. Exp. Psychol. Gen.* 140, 102–116
14. Nestojko, J.F. *et al.* (2013) Extending cognition to external agents. *Psychological Inquiry* 24, 321–325
15. Glenberg, A.M. (2010) Embodiment as a unifying perspective for psychology. *Wiley Interdiscip. Rev.: Cogn. Sci.* 1, 586–596
16. Clark, A. and Chalmers, D. (1998) The extended mind. *Analysis* 58, 7–19
17. Hutchins, E. (1995) *Cognition in the Wild,* MIT press
18. Cowley, S.J. and Vallée-Tourangeau, F. (2013) *Cognition Beyond the Brain: Computation, Interactivity and Human Artifice,* Springer
19. Kirsh, D. (1996) Adapting the environment instead of oneself. *Adapt. Behav.* 4, 415–452
20. Kirsh, D. (2010) Thinking with external representations. *Ai & Society* 25, 441–454
21. Carr, N. (2008) Is Google making us stupid? *Atlantic Monthly* 302, 56–62 July/August
22. Ballard, D.H. *et al.* (1997) Deictic codes for the embodiment of cognition. *Behav. Brain Sci.* 20, 723–742
23. Alibali, M.W. and DiRusso, A.A. (1999) The function of gesture in learning to count: more than keeping track. *Cognitive Dev.* 14, 37–56
24. Goldin-Meadow, S. and Wagner, S.M. (2005) How our hands help us learn. *Trends Cogn. Sci.* 9, 234–241
25. Alač, M. and Hutchins, E. (2004) I see what you are saying: action as cognition in fMRI brain mapping practice. *J. Cogn. Cult.* 4, 629–661
26. Jolicoeur, P. (1988) Mental rotation and the identification of disoriented objects. *Can J. Psychol.* 42, 461–478
27. Graf, M. (2006) Coordinate transformations in object recognition. *Psychol. Bull.* 132, 920–945
28. Risko, E.F. and Dunn, T.L. (2015) Storing information in-the-world: metacognition and cognitive offloading in a short-term memory task. *Conscious Cogn.* 36, 61–74
29. Melinger, A. and Kita, S. (2007) Conceptualisation load triggers gesture production. *Lang Cognitive Proc.* 22, 473–500
30. Dunn, T.L. and Risko, E.F. (2015) Toward a metacognitive account of cognitive offloading. *Cognitive Sci.* Published online August 26, 2015. http://dx.doi.org/10.1111/cogs.12273
31. Dunn, T.L. *et al.* (2016) Metacognitive evaluation in the avoidance of demand. *J. Exp. Psychol. Human.* Published online April 28, 2016. http://dx.doi.org/10.1037/xhp0000236
32. Schönpflug, W. (1986) The trade-off between internal and external information storage. *J. Mem. Lang.* 25, 657–675
33. Intons-Peterson, M.J. and Fournier, J. (1986) External and internal memory aids: when and how often do we use them? *J. Exp. Psychol-Gen.* 115, 267–280
34. Sparrow, B. *et al.* (2011) Google effects on memory: cognitive consequences of having information at our fingertips. *Science* 333, 776–778
35. Storm, B.C. and Stone, S.M. (2015) Saving-enhanced memory: the benefits of saving on the learning and remembering of new information. *Psychol. Sci.* 26, 182–188
36. Tversky, B. (2011) Visualizing thought. *Top. Cogn. Sci.* 3, 499–535
37. Tversky, B. (2015) The cognitive design of tools of thought. *Rev. Philos. Psychol.* 6, 99–116
38. Brandimonte, M.A. *et al.* (2014) *Prospective Memory: Theory and Applications,* Psychology Press
39. Einstein, G.O. and McDaniel, M.A. (1990) Normal aging and prospective memory. *J. Exp. Psychol. Learn.* 16, 717–726
40. Kliegel, M. and Martin, M. (2003) Prospective memory research: why is it relevant? *Int. J. Psychol.* 38, 193–194
41. McDonald, A. *et al.* (2011) Google calendar: a new memory aid to compensate for prospective memory deficits following acquired brain injury. *Neurosychol Rehabil.* 21, 784–807
42. Svoboda, E. and Richards, B. (2009) Compensating for anterograde amnesia: a new training method that capitalizes on emerging smartphone technologies. *J. Int. Neuropsych. Soc.* 15, 629–638
43. Gilbert, S.J. (2015) Strategic offloading of delayed intentions into the external environment. *Q. J. Exp. Psychol.* 68, 971–992
44. Uttl, B. and Kibreab, M. (2011) Self-report measures of prospective memory are reliable but not valid. *Can J. Psychol.* 65, 57–68

45. Landsiedel, J. and Gilbert, S.J. (2015) Creating external reminders for delayed intentions: dissociable influence on 'task-positive' and 'task-negative' brain networks. *NeuroImage* 104, 231–240
46. Wegner, D.M. (1995) A computer network model of human transactive memory. *Soc. Cognition* 13, 319–339
47. Harris, C.B. *et al.* (2014) Couples as socially distributed cognitive systems: remembering in everyday social and material contexts. *Memory Studies* 7, 285–297
48. Peltokorpi, V. (2008) Transactive memory systems. *Rev. Gen. Psychol.* 12, 378–394
49. Fisher, M. *et al.* (2015) Searching for explanations: how the internet inflates estimates of internal knowledge. *J. Exp. Psychol. Gen.* 144, 674
50. Ward, A.F. (2013) Supernormal: how the internet is changing our memories and our minds. *Psychol. Inq.* 24, 341–348
51. Wegner, D.M. and Ward, A.F. (2013) How Google is changing your brain. *Sci. Am.* 309, 58–61
52. Ferguson, A.M. *et al.* (2015) Answers at your fingertips: access to the internet influences willingness to answer questions. *Conscious Cogn.* 37, 91–102
53. Eskritt, M. and Ma, S. (2014) Intentional forgetting: note-taking as a naturalistic example. *Mem. Cognition* 42, 237–246
54. Payne, J.W. *et al.* (1988) Adaptive strategy selection in decision making. *J. Exp. Psychol. Learn.* 14, 534–552
55. Reder, L.M. (1987) Strategy selection in question answering. *Cognitive Psychol.* 19, 90–138
56. Walsh, M.M. and Anderson, J.R. (2009) The strategic nature of changing your mind. *Cognitive Psychol.* 58, 416–440
57. Marewski, J.N. and Schooler, L.J. (2011) Cognitive niches: an ecological model of strategy selection. *Psychol. Rev.* 118, 393–437
58. Karpicke, J.D. (2009) Metacognitive control and strategy selection: deciding to practice retrieval during learning. *J. Exp. Psychol-Gen.* 138, 469–486
59. Flavell, J.H. (1979) Metacognition and cognitive monitoring: a new area of cognitive-developmental inquiry. *Am. Psychol.* 34, 906–911
60. Arango-Muñoz, S. (2013) Scaffolded memory and metacognitive feelings. *Rev. Philos. Psychol.* 4, 135–152
61. Lovett, M.C. and Anderson, J.R. (1996) History of success and current context in problem solving: combined influences on operator selection. *Cognitive Psychol.* 31, 168–217
62. Patrick, J. *et al.* (2015) The influence of training and experience on memory strategy. *Mem. Cognition* 43, 775–787
63. Reder, L.M. and Schunn, C.D. (1996) Metacognition does not imply awareness: strategy choice is governed by implicit learning and memory. In *Implicit Memory and Metacognition* (Reder, L.M., ed.), pp. 45–78, Erlbaum
64. Schunn, C.D. *et al.* (2001) Awareness and working memory in strategy adaptivity. *Mem. Cognition* 29, 254–266
65. Gardony, A.L. *et al.* (2015) Navigational aids and spatial memory impairment: the role of divided attention. *Spatial Cognition & Computation* 15, 246–284
66. Gardony, A.L. *et al.* (2013) How navigational aids impair spatial memory: evidence for divided attention. *Spatial Cognition & Computation* 13, 319–350
67. Fenech, E.P. *et al.* (2010) The effects of acoustic turn-by-turn navigation on wayfinding. *Proc. Hum. Fact. Ergon. Soc. Annu. Meet.* 54, 1926–1930
68. Aporta, C. and Higgs, E. (2005) Satellite culture: global positioning systems, Inuit wayfinding, and the need for a new account of technology. *Curr. Anthropol.* 46, 729–753
69. Schryer, E. and Ross, M. (2013) The use and benefits of external memory aids in older and younger adults. *Appl. Cognitive Psych.* 27, 663–671
70. Roche, N.L. *et al.* (2002) Self-awareness of prospective memory failure in adults with traumatic brain injury. *Brain Inj.* 16, 931–945
71. Knight, R.G. *et al.* (2005) The effects of traumatic brain injury on the predicted and actual performance of a test of prospective remembering. *Brain Inj.* 19, 19–27
72. Cicerone, K.D. *et al.* (2000) Evidence-based cognitive rehabilitation: recommendations for clinical practice. *Arch. Phys. Med. Rehab.* 81, 1596–1615
73. Martin, T. and Schwartz, D.L. (2005) Physically distributed learning: adapting and reinterpreting physical environments in the development of fraction concepts. *Cognitive Sci.* 29, 587–625
74. Pouw, W.T. *et al.* (2014) An embedded and embodied cognition review of instructional manipulatives. *Educ. Psychol. Rev.* 26, 51–72
75. Hembree, R. and Dessart, D.J. (1986) Effects of hand-held calculators in precollege mathematics education: a meta-analysis. *J. Res. Math Educ.* 83–99
76. Ellington, A.J. (2003) A meta-analysis of the effects of calculators on students' achievement and attitude levels in precollege mathematics classes. *J. Res. Math. Educ.* 433–463
77. Novack, M.A. *et al.* (2014) From action to abstraction using the hands to learn math. *Psychol. Sci.* 25, 903–910
78. Paas, F. *et al.* (2003) Cognitive load theory and instructional design: recent developments. *Edu. Psychol.* 38, 1–4
79. Seli, P. *et al.* (2016) Mind-wandering with and without intention. *Trends Cogn. Sci.* 20, 605–617
80. Kingstone, A. *et al.* (2008) Cognitive ethology: a new approach for studying human cognition. *Brit. J. Psychol.* 99, 317–340
81. Risko, E.F. *et al.* (2016) Breaking the fourth wall of cognitive science real-world social attention and the dual function of gaze. *Curr. Dir. Psychol. Sci.* 25, 70–74
82. Shepard, R.N. and Metzler, J. (1971) Mental rotation of three-dimensional objects. *Science* 171, 701–703
83. Nelson, T.O. and Narens, L. (1990) Metamemory: a theoretical framework and new findings. *Psychol. Learn Motiv.* 26, 125–141
84. Siegler, R.S. and Lamaire, P. (1997) Older and younger adults' strategy choices in multiplication: testing predictions of ASCM using the choice/no-choice method. *J. Exp. Psychol. Gen.* 126, 71–92
85. Gray, W.D. and Boehm-Davis, D.A. (2000) Milliseconds matter: an introduction to microstrategies and to their use in describing and predicting interactive behavior. *J. Exp. Psychol. Appl.* 6, 322–335
86. Gray, W.D. *et al.* (2006) The soft constraints hypothesis: a rational analysis approach to resource allocation for interactive behavior. *Psychol. Rev.* 113, 461–482
87. Kool, W. *et al.* (2010) Decision making and the avoidance of cognitive demand. *J. Exp. Psychol. Gen.* 139, 665–682
88. Kurzban, R. *et al.* (2013) An opportunity cost model of subjective effort and task performance. *Behav. Brain Sci.* 36, 661–679
89. Henkel, L.A. (2014) Point-and-shoot memories the influence of taking photos on memory for a museum tour. *Psychol. Sci.* 25, 396–402
90. Macias, C. *et al.* (2015) Memory strategically encodes externally unavailable information. In *Proceedings of the 37th Annual Meeting of the Cognitive Science Society* (Noelle, D.C. *et al.*, eds), pp. 1458–1463, Cognitive Science Society
91. van Nimwegen, C. and van Oostendorp, H. (2009) The questionable impact of an assisting interface on performance in transfer situations. *Int. J. Ind. Ergonom.* 39, 501–508
92. Norman, D.A. (2013) *The Design of Everyday Things: Revised and Expanded Edition,* Basic books
93. Parasuraman, R. *et al.* (1993) Performance consequences of automation-induced 'complacency'. *Int. J. Aviat. Psychol.* 3, 1–23
94. Parasuraman, R. and Manzey, D.H. (2010) Complacency and bias in human use of automation: an attentional integration. *Hum. Factors* 52, 381–410
95. Wickens, C.D. *et al.* (2015) Using modeling and simulation to predict operator performance and automation-induced complacency with robotic automation: a case study and empirical validation. *Hum. Factors* 57, 959–975
96. Ebbatson, M. *et al.* (2010) The relationship between manual handling performance and recent flying experience in air transport pilots. *Ergonomics* 53, 268–277
97. Casner, S.M. *et al.* (2014) The retention of manual flying skills among airline pilots. *Hum. Factors* 56, 1506–1516

98. Kluge, A. and Frank, B. (2014) Counteracting skill decay: four refresher interventions and their effect on skill and knowledge retention in a simulated process control task. *Ergonomics* 57, 175–190

99. De Winter, J.C. *et al.* (2014) Effects of adaptive cruise control and highly automated driving on workload and situation awareness: a review of the empirical evidence. *Transportation research part F: traffic psychology and behaviour* 27, 196–217