A Fundamental Cognitive Taxonomy for Cognition Aids

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Objective: This study aimed to organize the literature on cognitive aids to allow comparison of findings across studies and link the applied work of aid development to psychological constructs and theories of cognition.

Background: Numerous taxonomies have been developed, all of which label cognitive aids via their surface characteristics. This complicates integration of the literature, as a type of aid, such as a checklist, can provide many different forms of support (cf. prospective memory for steps and decision support for alternative diagnoses).

Method: In this synthesis of the literature, we address the disparate findings and organize them at their most basic level: Which cognitive processes does the aid *need* to support? Which processes *do* they support? Such processes include attention, perception, decision making, memory, and declarative knowledge.

Results: Cognitive aids can be classified into the processes they support. Some studies focused on how an aid supports the cognitive processes demanded by the task (aid function). Other studies focused on supporting the processes needed to utilize the aid (aid usability).

Conclusion: Classifying cognitive aids according to the processes they support allows comparison across studies in the literature and a formalized way of planning the design of new cognitive aids. Once the literature is organized, theory-based guidelines and applied examples can be used by cognitive aid researchers and designers.

Application: Aids can be designed according to the cognitive processes they need to support. Designers can be clear about their focus, either examining how to support specific cognitive processes or improving the usability of the aid.

Keywords: cognitive aids, cognitive psychology, attention, memory, checklists, crisis checklists

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At the core of human factors psychology is the study of human capability and limitation, particularly the limitations of human cognition. This includes our limited memories, both working and long term, our limited attention, and our biases in judgment and reasoning, to name a few. Our ability to achieve as a species is partly due to our use of tools that allow us to overcome these limitations, from a recipe that turns the science of baking into a series of prompted steps to the checklists used by pilots in emergencies to the formal analysis of competing hypotheses that intelligence analysts use to prevent biased decisions. These tools can broadly be considered "cognitive aids," in that they provide support for the cognitive processes likely to fail during a complex or demanding task. The term cognitive aid first appeared in the 1970s (e.g., Hormann, 1971) and was often used to describe decision-support systems (e.g., Aldag & Power, 1986) before being used more generally to describe systems that supported other cognitive processes (e.g., Reason, 1987). However, results are mixed in the literature, with some reviews finding little or no benefit to introducing an aid (Bosk et al., 2009; Marshall, 2013) and others finding great benefit, hindered only by lack of aid adoption (Chaparro et al., 2019).

It is possible some of the mixed findings have been due to a focus on the form of the aid rather than its function. For example, cognitive aids have taken the form of checklists, maps, sensors, and automation (see Hales et al., 2008; Marshall, 2013; Myers, 2016, for various reviews). All of these formats could and do support a variety of cognitive processes, from different types of memory to visual attention, divided attention, and so on. Designing or comparing aids according to format misses the larger picture of the function of an aid: to support cognitive processes. Burian and colleagues suggested cognition must be considered to understand "why clinical checklists are or are not effective in different settings" (Burian et al., 2018). It is not surprising clinical checklists would not be effective if their function were to support the wrong cognitive process. For example, the original study of the WHO Surgical Safety Checklist noted that the step requiring patient and surgery site identification was a new procedure for some of the hospitals in their study (Haynes et al., 2009). For those sites, the checklist functioned to increase knowledge. At sites already using the procedure, it functioned to focus attention on the attributes of the surgical case. If the step were worded to support only the focus of attention by experts, and assumed the knowledge of how to check the identification of patient and site was present, those needing a knowledge aid might not benefit from the checklist. Thus, we agree with Burian and colleagues and extend the question beyond checklists to all cognitive aids. In this article, we propose to organize aids at their highest level: the type of cognition the aid should support. By doing so, we believe that new aids can be chosen or designed using well-established psychological theory and that the domain of cognitive aids will inform these theories. Essentially, a taxonomy of design choices can be created and tested to match the desired function of any cognitive aid.

REVIEW OF PREVIOUS TAXONOMIES

There have been efforts to classify cognitive aids according to useful categories, such as call-and-response checklists, "job aids," or medical cognitive aids (Hales et al., 2008; Marshall, 2013; Winters et al., 2009). These taxonomies were restricted to a domain (e.g., medicine or aviation) with implicit assumptions of the kinds of tasks prevalent in that domain. Indeed, important differences exist between application domains (Kapur et al., 2015). Context was not explicitly discussed in these taxonomies, perhaps because it was implicitly understood. For example, a taxonomy of checklists for the aviation domain considered "functions, format, design, length, usage, and the limitations of the humans who must interact with it" but not context or task type as a differentiator. However, it was likely assumed that the tasks were complex procedures in aviation and that the operators were already highly trained, making a posttask call-and-response checklist a beneficial option (Degani & Wiener, 1993). The posttask call-and-response checklist would not be suitable for other tasks, such as aiding first-time users of a cardiac defibrillator.

No taxonomy specified the cognitive processes being aided. Burian et al. (2018) made an important point concerning these taxonomies that the variety of cognitive aids that are called "checklists" have such varying attributes to make the term nondescriptive. For example, one checklist historically categorized as "medical" was not—it actually assisted doctors with business tax estimation (DeMuth & Achorn, 1978). Other medical checklists assisted teams during surgical procedures (World Health Organization [WHO], 2015) or provided decision support during cardiac arrests (Field et al., 2014). This is one reason the term cognitive aid is preferred—checklist denotes format, not function. Burian et al. (2018) presented a second taxonomy for medical checklists that characterized them by the types of cognition and actions they supported. Types of aids, such as critical event checklists or screening instruments, could be classified by their strengths: Were they designed more to aid memory or facilitate decision making? Were they needed in real time or after the fact? This was the only taxonomy to use cognitive processes and task demands as a classifier.

In sum, the previous taxonomies of cognitive aids focused on a particular field (e.g., medicine), often on a particular format (e.g., the checklist), and a particular focus (e.g., task type). This has practical value and offers a way to view the literature on cognitive aids. However, it is difficult to come to broader conclusions about the design of cognitive aids, particularly if the task to be aided is novel or differs from tasks with known successful aid designs. To develop a taxonomy informed by cognitive theories, we examined empirical articles investigating the effects of cognitive aids from 1998 to 2018 (literature review selection method detailed in McLaughlin & Byrne, 2019). What we found missing from these articles was consideration of the cognitive processes that are being aided.

Support of the Task by Cognitive Aid

The literature on cognitive aids can be divided into two areas of study: development and use of cognitive aids to help operators achieve an outcome (e.g., Kim & Dey, 2009) and studies on the usability of the aids (e.g., Clebone et al., 2019). In the literature, attributes of aid usability have been called contextual factors (Marmaras & Kontogiannis, 2001) and "event design elements" (Hepner et al., 2017). Without dividing the literature into studies of function versus usability, it is impossible to connect the cognitive process that the aid supports to outcome. For example, increasing the font size of a checklist may ease the perceptual demands of the operator when using the aid, but it would not ease the perceptual demands of the task for which the checklist was designed. We could not make conclusions about perception aids from such a study, though we could make usability conclusions regarding checklists. Unfortunately, the literature has not adopted this categorization. Figure 1 shows a sampling of the potential cognitive supports an aid may supply to an operator for achieving an outcome or making the cognitive aid easier to use. The processes that could be aided are known as limited cognitive resources: attention (Kahneman, 1973; Wickens, 2002), memory (Atkinson & Shiffrin, 1968), and perception (e.g., vision: Gibb et al., 2008; vestibular senses: Shappell et al., 2007). Also included were higher order processes affected by limited cognitive resources, such as decision making (De Martino et al., 2006) and learning/declarative knowledge (Stern, 2017). These processes form a theory-based start for the classification of aids, though there may be other processes that need to be added.

How Cognitive Processes Are Assisted by Cognitive Aids

Figure 1 lists a number of cognitive processes an aid could support. The list was meant to provide a starting point for categorizing the literature on aids by assessing which of these processes they were intended to support. Here, we provide examples of attentional aids from the literature. Gaps in the literature are discussed.

Attentional aids. It is generally accepted that attention is a limited resource composed of several fairly independent components (Navon & Gopher, 1979; Wickens, 2002). When a task or cognitive aid requires more resources than an operator possesses, performance declines. We provide an overview of aids supporting selective attention and orienting, divided attention, and sustained attention.

Selective attention is the ability to focus attention on important stimuli while ignoring others. This may mean to filter out distracting information (Broadbent, 1958) or that the distracting information is attenuated to the degree that it no longer consumes attentional resources (Treisman, 1964). Any aid supporting this cognitive process succeeds when it either helps to focus the operator on the important stimuli for the task or helps to inhibit the distracting stimuli in the task. Attentional *orienting* is a similar process, as attention is focused on a particular stimulus, with the small difference that there is the implication that an external cue caused the response, such as a flashing light to attract attention to a target (Müller & Rabbitt, 1989).

An aid can directly support noticing of cues in the task itself, leading to selective attention. For example, an aid might direct an operator to a cue needed for decision making as in the diagnosis of tension pneumothorax via the Stanford Anesthesia Aid: "Unilateral breath sounds, possible distended neck veins and deviated trachea (late signs)" (Howard et al., 2013). This directs attention toward cues that were potentially already present in the environment, but not noticed by the anesthesiologist. Many "job-aids" also support noticing in a task. For example, all warning systems and alarms direct attention, though memory recall is often required to interpret their meaning. In a European Space Agency project, augmented reality was implemented to aid noticing of warning signs and activity symbols while completing an ISS procedure for installing a temporary stowage rack (Helin et al., 2018). Most "crisis checklists" are also designed to support selective attention in the task (e.g., Goldhaber-Fiebert & Howard, 2013).

Other attentional cues can be provided within the aid to call attention to the structure, organization, or hierarchy of the aid. This supports usability of the aid. An example of attentional

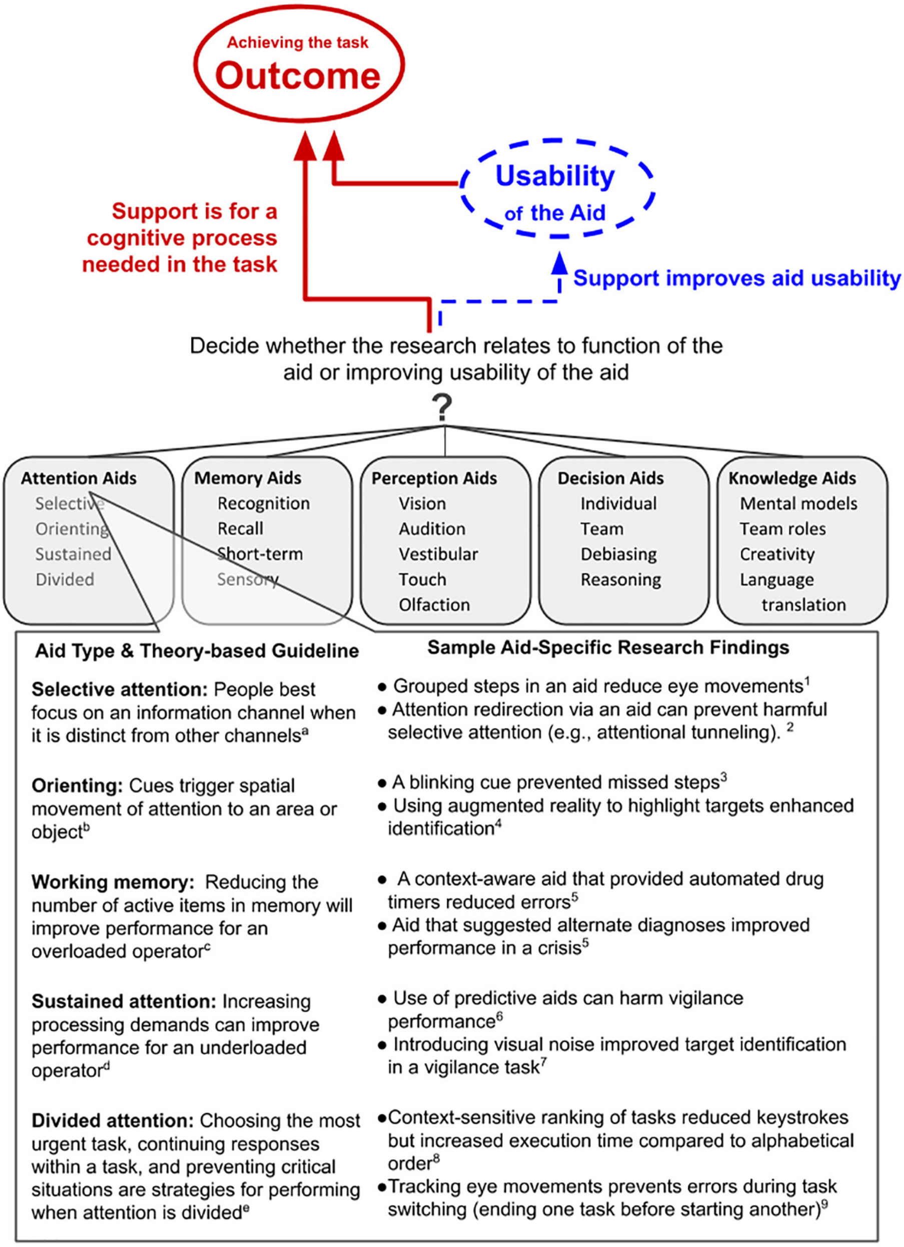

Figure 1. Model of a way to organize the literature on cognitive aids. Arrows show the potential support paths. Some support the task itself, such as supporting working memory by introducing an aid that collects and presents only the information necessary for a decision. Other supports may make the aid itself easier to use, such as increasing the contrast or font size of the aid interface. A detailed explanation of how the literature on aids could be presented is shown for attention aids. The same treatment may be given to the other cognitive processes that aids can support. [a]Treisman (1964); [b]Folk and Gibson (2001); [c]Wickens, Hollands et al. (2015); [d]Healy and Bourne (2013); [e]Rill et al. (2018); [1]Clebone et al. (2019); [2]Long et al. (2017); [3]Chung and Byrne (2008); Rusch et al. (2013); [5]Wu et al. (2014); [6]Minotra and McNeese (2017); Bodala et al. (2016); [8]Ramachandran et al. (2014); [9]Ratwani and Trafton (2011).

capture through usability improvements can be found in the WHO Surgical Safety Checklist (Haynes et al., 2009). The design of the checklist includes color-blocked backgrounds that divide the checklist into sections. Inside these sections, broad horizontal lines delineate subsections. Bold font denotes roles and actions. It is expected that attention moves back and forth between the checklist and the task, with these attentional cues aiding in visual reorientation to the aid. Wu et al. (2014) compared standard text, structured text, color block, pictographs, and interactive focus with expert users: eye tracking revealed how the color block design drew the user's gaze to the block that contained the information, even when looking back and forth from the primary task.

Divided attention means to distribute attention to *n* simultaneous tasks. Models of task switching help predict how an operator will respond to multiple task demands (Barg-Walkow & Rogers, 2017; Wickens & Gutzwiller, 2017) and this knowledge can be used in cognitive aid design. Such models suggest the importance of context-sensitive aid design, where notifications and alarm salience are adjusted according to the current importance of a task (e.g., Abdi et al., 2015). In the most notorious aviation example, an alarm regarding an interior light malfunction overcame the salience of a terrain warning system, resulting in a crash (Wiener, 1977). Eye tracking can also be used to detect when a task is or will be neglected, allowing an aid to prompt the return of attention to that task (Ratwani & Trafton, 2011). However, there is still much to be learned and implemented regarding aids for divided attention: Alarm fatigue (e.g., Kobayashi et al., 2017) and ineffective multitasking (Ralph et al., 2014) are still common issues.

Sustained attention, also called vigilance, is the process of maintaining alertness over periods of time (Davies & Parasuraman, 1982). Aiding sustained attention often means to reduce the need for it, via alarms (e.g., Fletcher & Bedwell, 2014), or other ways to augment slowly changing or rare stimuli that might be overlooked (Rall et al., 2010). Ironically, aids that support operators well can actually put more load on the operator's sustained attention resources. When cognitive aids predict events or outcomes, the operator may come to depend on that prediction and miss critical events not predicted by the aid (Minotra & McNeese, 2017). This is similar to the paradox of automation—when highly automated and reliable systems fail, it is more likely the failure will go unnoticed than in less automated or reliable systems (e.g., Bainbridge, 1983).

Another form of vigilance aid would be a *cognitive antidote* (Healy & Bourne, 2013): an increase in task difficulty or the addition of another task to keep the operator engaged. However, the limits, effectiveness, and possible detrimental effects of cognitive antidotes have not been studied regarding cognitive aids. There was little in the literature regarding cognitive aids for vigilance tasks with the exception of a study introducing visual noise in a virtual world (e.g., heavy rainfall) as an aid to maintaining vigilance for longer time periods (Bodala et al., 2016). The lack of research on cognitive antidotes is brought to light when an aid taxonomy highlights known cognitive processes and the (lack) of accompanying research.

To support *working memory* means to support attentional control and manipulating information in memory. When an aid directly supports the task via support of working memory, this usually means that the aid holds the information to be used in the task in an easily accessible format, so that information can be integrated and used by the operator. Most of the healthcare aids, particularly "handoff" aids for transitioning patients between care teams, supported the working memory of the operators by calling for the information crucial to clinical decisions and organizing that information for the operator (e.g., Weiss et al., 2013). Categorizing these aids as working memory aids was done post hoc, as studies do not currently report specific ways aids support cognition.

Case Study of Applying the Taxonomy

Miller et al. (2000) introduced three different cognitive aids designed to improve aircraft identification by military radar operators who had difficulty knowing whether they had previously identified an aircraft. Here, we retrospectively discuss one of those aids in terms of the cognitive processes it supported. Aids were created to play a tone any time a new aircraft entered the display, use colors to mark an airplane as identified, and provide a symbol to indicate which aircraft needed to be identified quickly. The tone and colors supported *selective attention* by indicating which aircraft were already identified; the operator could selectively attend only to the unidentified aircraft. The tone and symbol for important targets supported *orienting* by drawing attention to specific targets. The combined cues supported *working memory* by placing the variables to be considered in aircraft identification "in the world" rather than relying on them being kept active "in the head" of the operator (Norman, 2013). Choosing color and sound as the methods of support was the usability consideration for the use of the aid.

DISCUSSION

The terms checklist, procedure, and cognitive aid have little meaning on their own, even when broken down into subtypes, such as "call and response" or "emergency procedure" or "decision aid." This is because any task that requires an aid is likely complicated enough to necessitate multiple forms of cognition support. We provide a general structure of categorization, where any single aid is broken down into how it provides support for multiple processes. A surgical checklist, for example, might provide information support via one step where all team members must announce their name and role, but in other steps, it might provide decision support for actions to take in event of heart or lung stoppage (McLaughlin et al., 2016). Another type of aid, role cards attached to surgical team members, would provide the same information support as the aforementioned checklist could, but is not a checklist (Renna et al., 2016). A different checklist might provide none of those supports (WHO, 2015). We propose comparing aids via the cognitive supports they provide. This will allow comparison across aids, whether those aids be checklists, flowcharts, static or dynamic, or any of the other labels used to describe cognitive aids. Aid researchers and designers can turn to the literature for guidelines on supporting the cognitive processes in their task of interest and see specific design choices others have attempted and their ramifications.

Application

Our method of classification is similar to (and depends on) task analysis. A complete understanding of the outcome desired and the demands of the task preceding that outcome is the crucial first step toward developing new cognitive aids. With a complete task analysis, task demands can be matched to the kind of cognitive support required. Using previously classified aids, types of previously successful support can be nominated for use in a new aid. For example, if the task has prospective memory demands, the aid should support prospective memory using evidence-based designs: alarms, notifications, or checklist steps. An organized literature will allow practitioners to consider previous aid designs during their design process.

Though such classification of aids will organize the literature and allow easier comparisons of studies and the development of new aids, it is not the only important piece of the picture. As previous taxonomies discussed, the designers of any aid and its components must consider the support options in terms of the functional task environment: "the moment-to-moment intersection of a cognitive agent (human operator) pursuing a particular goal in a particular physical environment" (Gray et al., 2006, p. 101). As mentioned by Hales et al. (2008), aid design interacts with the limitations of physical storage and use location. For example, there are many ways to provide attentional support (checklist items, automated sensors, lights, or other electronic notifications) but not every option can be implemented in every task environment. Further attributes of the user–task–environment system include individual differences in the operator's knowledge, skills, and abilities and the criticality of the task (e.g., Marshall, 2017).

Limitations

There are limitations with using cognitive processes to describe cognitive aids. First, task analysis requires knowledge of cognition beyond many of those currently creating cognitive aids. Thus, translation by experts will be needed once the taxonomy offers insight into the various ways a task can be supported by cognitive aids. This has been the historical role of human factors professionals, to bridge the knowledge gap of operators or users and designers. A second limitation will be the overlap as to which portions of an aid offer which support. For example, the Surgical Safety Checklist requires the nurse to verbally confirm "completion of instrument, sponge and needle count" before the patient leaves the operating room. This could be argued to support *prospective memory* for the surgeons' intent to remove those items or *recognition memory*, that all items in a tray are indeed in the tray, or *orienting attention*, to ensure that the nurse focused on the tray at the correct time, or all of these combined.

Our last limitation was that only attention aids were fully explained; a similar treatment must be applied to other cognitive processes. Our model provides the structure; research findings and gaps must be established for the other cognitive processes. Research on cognitive aids should include consideration of possible interactions when more than one cognitive process requires support in a task.

Conclusion

A complete understanding of the outcome desired and the demands of the task preceding that outcome is the crucial first step toward developing new cognitive aids. With task analysis, task demands can be matched to the kind of cognitive support required. Using previously classified aids, the types of previously successful support can be nominated for use in a new aid. For example, if the task has prospective memory demands, the aid should support prospective memory using evidence-based designs: alarms, notifications, checklist steps, and look to other aids that were classified as providing prospective memory support for novel ideas.

KEY POINTS

- The literature on cognitive aids can be organized through analysis of what cognitive processes the aid supports.
- Aids can be improved by altering how the aid supports the task or by improving the usability of the aid.
- Considering the individual cognitive processes and interactions being supported by aids provides those making new aids a connection to well-established theories in cognitive psychology.
- The proposed method for future aid design includes thorough analysis of the task to be aided in terms of resource-limited cognitive processes followed by theory and evidence-based design using an organized literature on cognitive support via aids.

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