Human-Centered Design Meets Cognitive Load Theory: Designing Interfaces that Help People Think

Sharon Oviatt[§]
Incaa Designs
821 Second Avenue, Suite 1100
Seattle, WA 98104 USA
+1 206-428-0726

oviatt@adapx.com

[§]Also at OHSU

ABSTRACT

Historically, the development of computer systems has been primarily a technology-driven phenomenon, with technologists believing that "users can adapt" to whatever they build. *Human-centered design* advocates that a more promising and enduring approach is to model users' natural behavior to begin with so that interfaces can be designed that are more intuitive, easier to learn, and freer of performance errors. In this paper, we illustrate different user-centered design principles and specific strategies, as well as their advantages and the manner in which they enhance users' performance. We also summarize recent research findings from our lab comparing the performance characteristics of different educational interfaces that were based on user-centered design principles. One theme throughout our discussion is human-centered design that *minimizes users' cognitive load*, which effectively frees up mental resources for performing better while also remaining more attuned to the world around them.

Categories and Subject Descriptors

H.5.2 **[Information Interfaces and Presentation]**: User Interfaces—*user-centered design, interaction styles, evaluation/methodology, input devices and strategies, prototyping.*

General Terms

Design, Human Factors, Performance.

Keywords

Human-centered design, cognitive load, performance metrics, usability, robustness, educational interfaces, multimodal interfaces, tangible interfaces, pen-based interfaces, spoken language interfaces, mobile interfaces.

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1. INTRODUCTION TO HUMAN-CENTERED DESIGN

In a recent article sent from Lima Peru, Tom Friedman of the *New York Times* ponders whether we have evolved from the Iron Age to the Industrial Age to the Information Age to the *Age of Interruption,* in which the "malady of modernity" is that we are now all afflicted with chronic multi-tasking and *continuous partial attention* induced by cell phones, email, the internet, handhelds, and our other many devices. In a contemplative mood stimulated by his trip through the rain forest, he wonders whether the Age of Interruption will lead to a decline of civilization as our ideas and attention spans shrink like slugs sprinkled with salt, and civilization at large gets collectively diagnosed with Attention Deficit Disorder. Friedman then asks the obvious question that we've all been wondering about, which is *"Who can think or write or innovate under such conditions?"*

As an antidote to this malady, Friedman describes Gilbert his rain forest guide who:

> "carried no devices and did not suffer from continuous partial attention. Just the opposite. He heard every chirp, whistle, howl or crackle in the rain forest and would stop us in our tracks immediately and identify what bird, insect or animal it was. He also had incredible vision and never missed a spider's web, or a butterfly, or a toucan, or a column of marching termites. He was totally disconnected from the Web, but totally in touch with the incredible web of life around him." —Friedman, 2006 [10]

In Section 3 of this paper, we summarize recent research that confirms Friedman's concerns about technology-induced continuous partial attention, and its deleterious impact on people's ability to perform. In a study comparing different interfaces, high school students who used traditional graphical interfaces that distracted their focus of attention the most while solving geometry problems also showed the greatest selective decline in *high-level meta-cognitive skills*. In addition, they worked more slowly, made more errors, and failed to remember the work they had just finished [26, 27]. In light of these findings, one might ask who is designing interfaces for Gilbert and the rest of us, who need to perform but also stay connected to the web of life? And what is *human-centered design,* anyway?

1.1 Human-Centered Modeling and Design

Historically, the development of computer systems has been primarily a technology-driven phenomenon, with technologists believing that "users can adapt" to whatever they build. As a result, they typically have relied on instruction, training, and practice with an interface to encourage users to interact in a manner that matches a system's processing capabilities. *Human-centered design* advocates that a more promising and enduring approach is to model users' natural behavior to begin with, including any constraints on their ability to attend, learn, and perform, so that interfaces can be designed that are more intuitive, easier to learn, and freer of performance errors. The potential impact of this approach is substantial improvement in the commercial viability of next-generation systems for a wide range of real-world applications.

1.1.1 Human-Centered Interface Strategy: Example 1

To advance next-generation interfaces, human-centered design that incorporates cognitive science, linguistics, and other areas involving multidisciplinary expertise becomes an inescapable requirement. As a case in point, the design of spoken, pen-based, and multimodal systems requires modeling modality-specific features and communication patterns upon which the system must be built. For example, disfluencies and hyperarticulation are landmark features of interactive speech, which are important to recognize because they are difficult for systems to process. People also have many highly automatized behaviors, such as speech prosody and timing, which are organized in modality-specific brain centers and not under full conscious control. Given these challenges, one human-centered strategy for proactively designing such systems is to:

- Identify and model major sources of variability in human input that the system must process, especially difficult-to-process ones
- Devise interface techniques capable of effectively but transparently reducing these difficult sources of variability, thereby enabling more robust system processing [21]

For example, a structured form-based interface can eliminate up to 80% of all the disfluencies that *the same person completing the same task* would have uttered using a less constrained interface [20]. This is because disfluencies are strikingly sensitive to the increased planning demands of speaking progressively longer utterances, which increases their cognitive load substantially. A form-based interface simply elicits briefer constructions from the user so that disfluent input is minimized, although users typically are completely unaware of their disfluencies or the impact of the interface. One beauty of this human-centered design approach is that interruptive system error messages are nearly eliminated, because errors are avoided.

In short, a human-centered design approach can leverage a more usable and robust system by modeling users' pre-existing behavior and language patterns, rather than attempting to retrain strongly entrenched patterns. It also can transparently guide users' input toward processability, using techniques that are neither noticed nor objectionable. One future challenge in areas such as mobile, ubiquitous, and multimodal-multisensor interfaces is for human-centered design to adequately model human communication and activity patterns more broadly, as well as usage contexts.

1.1.2 Human-Centered Interface Strategy: Example 2

A second general human-centered design strategy associated with multimodal interfaces is to:

- Model users' natural multimodal communication patterns
- Build a fusion-based multimodal interface that gives users the flexibility to exercise their own intuitions about when to use one mode, the other, or both, thereby leveraging greater robustness [25]

Human-centered design of multimodal interfaces acknowledges that people are experienced at communicating multimodally and know when to use a particular mode to communicate accurately. They will use the input mode they judge to be least error prone for conveying specific lexical content, including switching modes if an error is encountered [23]. Their language also can be simpler and easier to process when communicating multimodally rather than unimodally. In a telecommunications study, error analyses revealed that up to 86% of all task-critical errors could be avoided simply by making a second input mode available to people [24]. All of these are user-centered reasons why multimodal interfaces support substantially improved error avoidance and recovery [22, 23, 25].

Apart from error handling, users respond to dynamic changes in their own working memory limitations and cognitive load by shifting to more multimodal communication as load increases with task difficulty [28]. As a result, a flexible multimodal interface supports users in *self-managing their cognitive load* and minimizing related performance errors while solving complex real-world tasks [22, 28]. In summary, the human-centered design of multimodal interfaces enables users to adapt effectively in a way that expands their range of computer-supported problem solving abilities.

Other complementary and important user-centered design approaches involve user-adapted (e.g., to expertise level, native language) and real-time adaptive interfaces (e.g., to a user's current focus of attention), in which the system adapts to specifics of the user and his or her performance status. From a user-centered design perspective, we know that users can and do adapt more to systems than the reverse. Nonetheless, as adaptive systems become more common and increase in utility and sophistication, the long-term research agenda will be the development of *mutually adaptive* human-computer interfaces [30].

1.2 Design Principles for Enhancing Users' Performance

The two examples above illustrate a human-centered interface design approach to modeling naturally-occurring behavior, with an emphasis on predictive modeling that elucidates the basis for error-prone or hard-to-process behavior. They also illustrate interface design strategies for transparently guiding user behavior to be more compatible with system processing capabilities, for leveraging from users' expertise, and for creating interfaces that enable users to adapt to changing task demands. One theme throughout these human-centered design examples is design that *minimizes users' cognitive load* by supporting performance while eliminating unnecessary distraction.

The following are user-centered design principles associated with improved human performance. The first four principles were illustrated in Section 1.1. The last four principles will be discussed in Section 3, which presents recent research findings from our lab comparing the performance characteristics of different educational interface designs. These principles include developing interfaces that:

- Leverage from users' experience, knowledge, and engrained behavioral patterns, as well as adapting to users' behavior and preferences
- Support users' natural and flexible multimodal communication patterns
- Transparently guide users' input to minimize difficult sources of linguistic and behavioral variability, so system errors are reduced and usability is enhanced
- Minimize cognitive load associated with user input planning (e.g., producing lengthy sentences)
- Accommodate users' existing familiar work practice, rather than attempting to change it
- Support representational systems as part of the interface (e.g., linguistic, diagrammatic, symbolic, numeric) that users need to perform their task
- Minimize cognitive load associated with extraneous complexity of system output (e.g., unnecessary features that distract users' attention when completing a task)
- Minimize interruptions (i.e., whether due to distracting system features or explicit system interruptions), which undermine users' ability to engage in high-level planning, integrative thinking, and problem solving

2. COGNITIVE LOAD THEORY

Sections 2.1-2.2 outline background information on cognitive load, its theoretical underpinnings, and assessment strategies. Section 3 then presents recent research findings from our lab on the application of cognitive load theory to high-performance educational interface design, which is centered on modeling of students' performance.

2.1 Cognitive Load and Theoretical Underpinnings

One theme throughout the discussion of human-centered design principles, strategies, illustrations, and research findings is a focus on cognitive load and how to minimize the extraneous cognitive load that users experience due to an interface. Cognitive load is a global term, which refers to the mental resources a person has available for solving problems or completing tasks at a given time. It is a multi-faceted concept, since tasks, individual differences, and social and environmental factors all influence the actual cognitive load experienced by a person. Compared with the global concept of "workload" used in the past, which encompasses mental and physical exertion, more recent research has focused on the cognitive aspects of load and has emphasized *limited attention and working memory capacity* as specific bottlenecks that continually exert load during human information processing [5, 6, 12, 13, 26, 33, 34, 36, 37].

Cognitive Load Theory (CLT) and its cognitive science underpinnings provide a coherent and powerful basis for predicting performance when using alternative interfaces, and for designing interfaces that effectively minimize cognitive load [5, 6, 17, 26, 31, 33-37]. Advocates of CLT assess the "extraneous complexity" associated with an interface separately from the "intrinsic complexity" associated with the user's main task, which is done by comparing performance indices of cognitive load as people use different interfaces. As such, CLT focuses on designing interfaces that *decrease extraneous cognitive load* so people's available intellectual resources can be devoted to their main task, which may be navigating on foot, driving, or learning a new subject matter.

Cognitive Load Theory has been used extensively within education to predict students' performance when using new educational materials and interfaces, and to design educational interfaces that effectively minimize students' load so they can focus on their primary learning task [16, 17, 26, 31, 35]. When learning new intellectual tasks, the cognitive effort required by learners tends to be high and to fluctuate substantially, so managing students' load has been viewed as an important theme. Basically, CLT has maintained that in the process of learning it is easier to acquire new schemas and to effectively automate them if instructional methods minimize demands on a student's working memory, thereby reducing cognitive load [5, 17, 26, 31, 35]. To achieve this, educators have used CLT to compare performance indices of load as students use different interfaces so instructional materials can be designed that leave students' intellectual resources available for learning tasks.

The main theoretical foundations of Cognitive Load Theory originally were established by Wickens' and Baddeley's work, which provided the basis and perspective needed to guide the work described in education and interface design. *Multiple Resource Theory*, developed by Wickens and colleagues, clarified that there can be competition between modalities during tasks (e.g., manual/verbal user input, auditory/visual system output), such that the human attention and processing required during input and output result in better performance if information is distributed across complementary modalities [36, 37]. For example, during "time-shared performance" verbal input is more compatible with visual than auditory system output. This theory states that cross-modal time-sharing is effectively better than intra-modal time-sharing.

In related theoretical work illustrated in Figure 1, Baddeley presented a *Theory of Working Memory* which maintains that short-term or working memory consists of multiple independent processors associated with different modes [5, 6]. According to this theory, a visual-spatial "sketch pad" maintains visual materials such as pictures and diagrams in one area of working memory, while a separate phonological loop stores auditory-verbal information. Although these two processors are believed to be coordinated by a central executive, in terms of lower-level modality processing they are viewed as functioning largely independently, which is what enables the effective size of working memory to expand when people use multiple modalities during tasks. The central executive plans future actions, initiates retrieval of long-term memories, integrates new information and decision-making processes, and so forth.

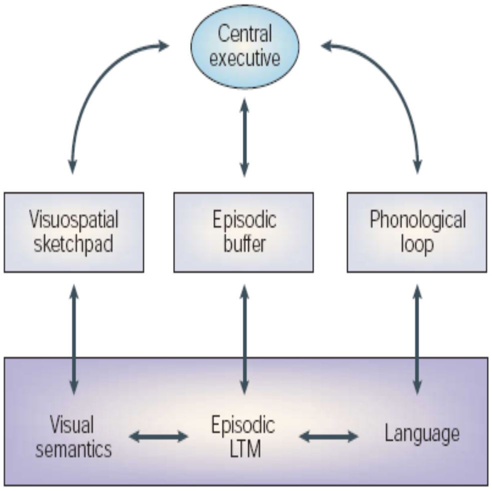


Figure 1. Schematic of Baddeley's multi-component theory of working memory, with a summary of long-term or crystallized knowledge (bottom level), separate short-term modality stores for receiving and rehearsing visual and auditory information (middle level), and the episodic buffer coordinating these short-term stores with both long-term memory and the central executive (top level).

2.2 Cognitive Load Metrics and Assessment Strategies

Physiological, performance-based, and self-assessment techniques all have been used to measure cognitive load [9, 13, 31], although performance-based measures primarily have been used in the context of interface design. Performance metrics can be evaluated in real time, and used in field and mobile contexts [12, 19, 26, 31]. In addition, they are relatively objective, sensitive, and reliable metrics, which are capable of reflecting task performance behaviors of direct interest and also validating the difficulty level of tasks. Typical performance measures of cognitive load have included time to complete tasks, reaction time, correct solutions, memory retrieval time and correctness, time estimation, rate of physical activity and speech, spoken disfluencies, multimodal integration patterns, and other indices [12, 18, 20, 26, 29, 31]. In contrast, subjective measures of cognitive load interrupt a person's work and cannot be collected as real-time measures [9]. The more promising physiological measures for assessing cognitive load, such as brain activity reflected in EEGs and evoked potentials (e.g., P-300) or eye monitoring of pupil size, require special instrumentation, are easily contaminated by movement and variables other than cognitive load, and are not yet compatible with field and mobile assessment [9, 13].

The most common research strategy for examining cognitive load has been divided attention or dual-task studies, in which the person completes a primary task while also monitoring and responding to a secondary task. While many studies have involved artificial laboratory tasks, others have entailed complex and realistic ones that are relevant to interface design (e.g., navigating on foot while using a handheld device [19]). One advantage of dual-task methodologies is that performance on the secondary task can provide a very sensitive assessment of spare mental capacity remaining due to the "extraneous load" exerted by the interface, which can be useful in deriving comparative interface design information and diagnostics. Dual-task methods are especially relevant and ecologically valid when applied to field and mobile interface design, which chronically involve multitasking and divided attention.

3. APPLICATION OF COGNITIVE LOAD THEORY TO EDUCATIONAL INTERFACE DESIGN

Recently, the concept of cognitive load has been applied to the development and comparative assessment of system interfaces in order to improve the performance characteristics of mobile, educational, and other interfaces [12, 18, 19, 26]. As work on this topic has expanded, research has become interested in quantifying cognitive load, and in refining our understanding of how cognitive load is generated and manifested during different phases of *dynamic information processing* [7, 26, 31]. In addition, recent research has aimed to predict what the net impact of cognitive load will be on humans' ability to perform, so that computers can be designed that minimize load and expedite performance and safety, especially in field and mobile situations [12, 19, 26].

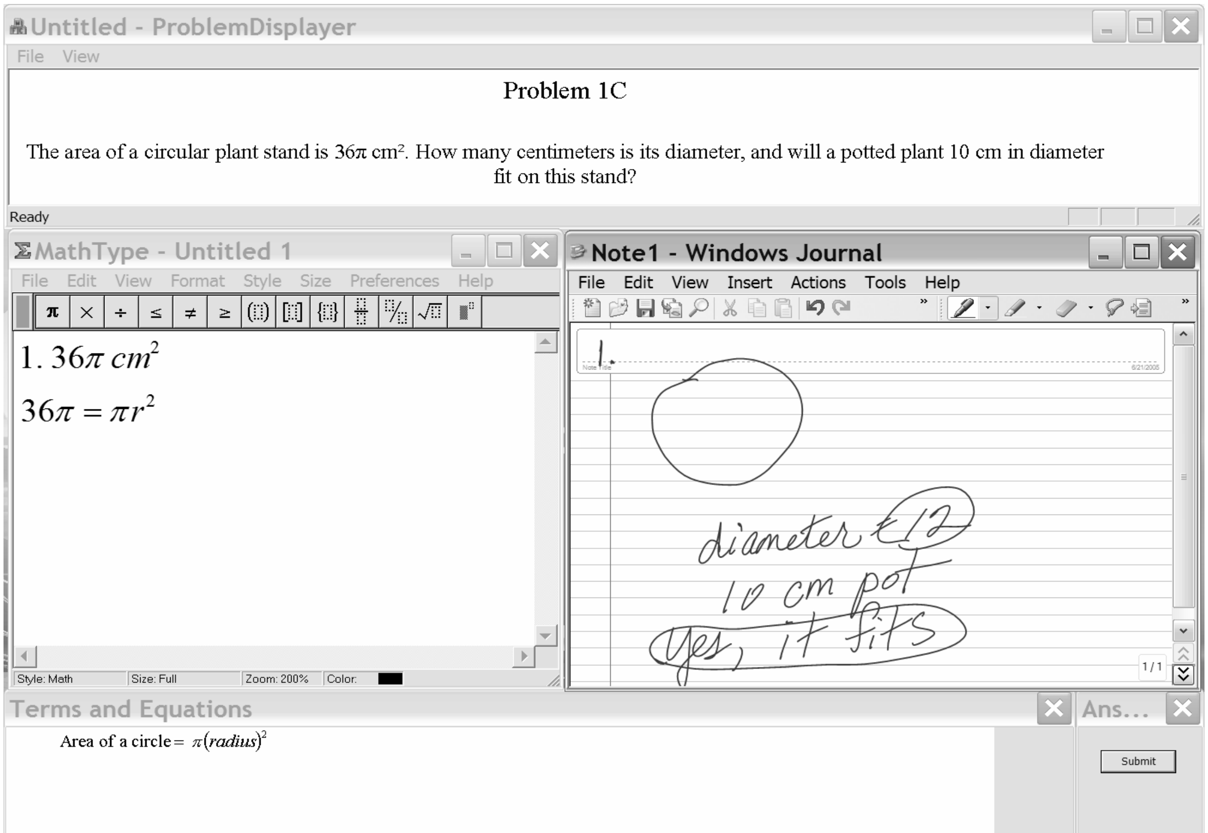
In previous education experiments, a *multimodal presentation format* was shown to expand the size of students' available working memory, such that they were able to solve geometry problems better multimodally than when using a single mode [17]. In other research with elementary school children and adults, *active manual gesturing* was demonstrated to reduce cognitive load and improve memory during a task requiring explanation of math solutions. Furthermore, during more difficult tasks the impact of gesturing on alleviating cognitive load and improving memory was magnified [11]. The physical activity of manual or pen-based gesturing is believed to play a particularly important role in organizing and facilitating people's spatial information processing, reducing cognitive load on tasks involving geometry, maps, and similar areas [2, 22].

3.1 Educational Interface Study: Goals and Methods

A very recent study in our lab compared non-computational work practice for mathematics education, which still involves paper and pencil (PP), with different interface alternatives. The general goal of this research was to prototype promising new interface directions for math education, and to compare their ability to support students' performance during math problem solving activities. Comparisons were made of these interfaces: (1) an

Anoto-based digital stylus and paper interface [4] (DP), (2) a pen tablet interface with stylus input (PT), and (3) a graphical tablet interface with keyboard, mouse, and stylus input, which was enhanced with a simplified MathType equation editor (GT). In particular, the study evaluated whether student performance would *deteriorate as interfaces departed more from students' existing work practice* (GT > PT > DP), with lower-performing students experiencing greater cognitive load and performance degradation than high-performing students when using the same interfaces. Cognitive Load Theory was used to provide a framework for predicting the rank ordering of interfaces according to their ability to minimize students' cognitive load and enhance their performance.

Twenty high school students, who were classified as either low- or high-performing in geometry, completed problems varying in difficulty from easy to very hard. Each student completed geometry problems using paper and pencil as well as all three interfaces, so that within-subject comparisons could be made of performance. The math problems were word problems that required translation from linguistic information into diagrams, digits, and symbols in order to solve them. As a result, successful completion of the math problems required complex problem solving using linguistic, symbolic, numeric, and diagrammatic representational systems, as well as translation among them. This permitted testing the ability of different interfaces to support broad and flexibly expressive user communication patterns, which are required for realistic problem solving in domains like geometry.



Problem 1C

The area of a circular plant stand is 36π cm². How many centimeters is its diameter, and will a potted plant 10 cm in diameter fit on this stand?

1. $36\pi\ cm^2$

$36\pi = \pi r^2$

1.

diameter = 12

10 cm pot

Yes, it fits

Area of a circle = $\pi(radius)^2$

Figure 2. Student interface used to display math problems.

Figure 2 shows an example problem (top) presented on a Toshiba Portege laptop screen. This was used to display the problems during all four conditions, along with any terms or equations required to complete the problem (lower left). While working on their problems, each student wore a close-talking headset that recorded speech digitally during a think-aloud protocol. The headset was used to collect data on students' focus of attention, including whether they were thinking about *low-level procedural math issues* while working (e.g., immediate computational steps required to solve the problem), *high-level meta-cognitive issues* involved in guiding their math solution (e.g., knowing if the problem was a 2D or 3D geometry problem, or if an error had occurred), or were *distracted by interface issues* associated with the tools they were using (e.g., mis-clicking with the mouse). Students also completed a forced-choice memory test, in which they were asked to recall information from the math problems they had just finished solving. In addition to evaluating students' focus of attention, meta-cognitive control, and memory, other behaviors involved in dynamic information processing were assessed including their task completion speed, fluency of linguistic expression, and math solution correctness. Collectively, these measures reflected and provided rich insights into students' level of cognitive load while they worked on a realistic range of math problems. Further details of the research methods are outlined elsewhere [26, 27].

3.2 Educational Interface Study: Results and Discussion

The results of this study revealed that the *same students completing the same geometry problems* experienced greater load and performance deterioration as interfaces departed more from existing work practice (GT > PT > DP). That is, students performed better when using a digital stylus and paper interface than a pen tablet interface, which in turn supported better performance than a graphical tablet interface. In addition, lower-performing students experienced elevated cognitive load, with the more challenging interfaces (GT, PT) disrupting their performance disproportionately more than for higher performers. This rank ordering of interfaces was evident from the pattern of convergent results reflected by the performance indices, which together showed corresponding degradation in students' speed, attentional focus, meta-cognitive control, correctness of problem solutions, and memory during their work [26, 27]. These results are presented and discussed individually in this section, and also summarized in Figure 10.

As shown in Figure 3, students were significantly faster when using the digital stylus and paper interface (i.e., the *tangible paper-based interface*) than either of the tablet interfaces. In fact, they completed problems as quickly using this interface as with paper and pencil. Likewise, and as illustrated in Figure 4, students were significantly more attentive to their math (i.e., less distracted by the interface) when using the digital stylus and paper interface than either of the tablet interfaces. As shown in Figure 5, low-performing students also remembered math information better after using the digital stylus and paper interface than either of the tablet interfaces. All of these statistically significant differences reveal advantages of *tangible paper-based interfaces over tablet-based ones* [26].

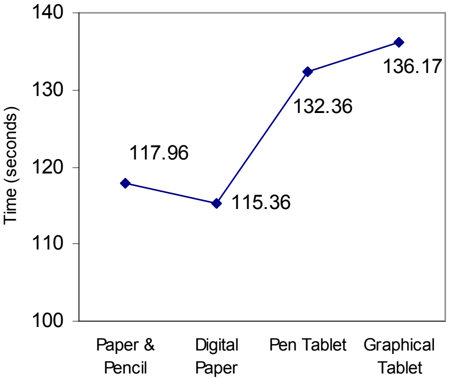


Figure 3. Average total time to complete individual math solutions using different interfaces.

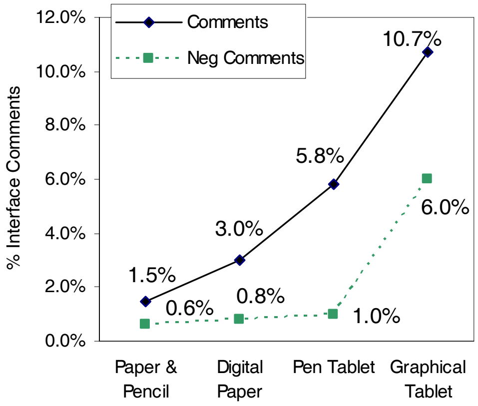


Figure 4. Average percent of interface comments and negative interface comments of the total when using different interfaces.

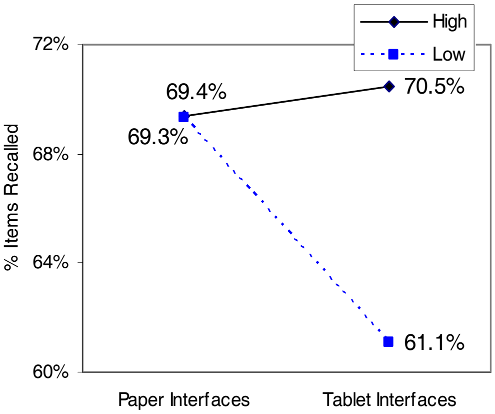


Figure 5. Percent of items recalled correctly by low- and high-performing students in the paper- (PP, DP) versus tablet-based (PT, GT) interfaces.

On the other hand, Figure 6 shows that the two *pen-based interfaces* (DP, PT) supported better meta-cognitive control of students' work (i.e., indicated by high-level math comments) than the graphical tablet interface (GT). Figure 7 also shows that the pen-based interfaces supported more planning (i.e., indicated by

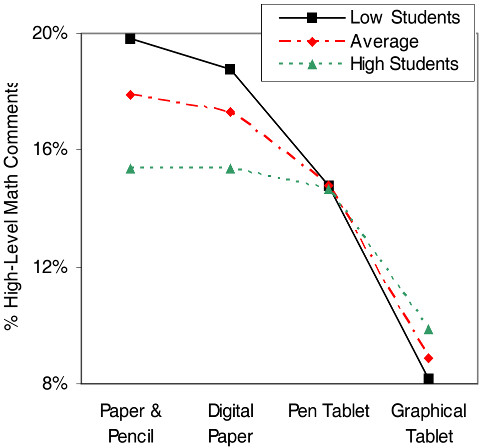


Figure 6. Average percent of high-level math comments of the total for low- and high-performing students when using different interfaces.

advance diagramming) than the GT interface. In addition, low-performing students solved more problems correctly with the pen-based interfaces, as illustrated in Figure 8. Finally, as shown in Figure 9, high-performing students expressed themselves more fluently with the pen-based interfaces (i.e., using symbolic, diagrammatic, linguistic, and numeric representational systems). All of these statistically significant differences reveal advantages of *pen-based interfaces over the traditional graphical tablet interface* [26].

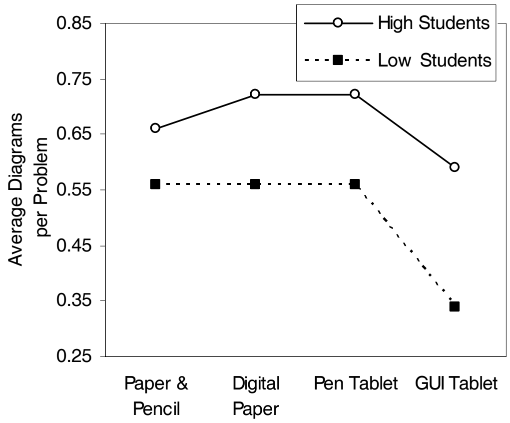


Figure 7. Average number of diagrams per problem as a function of interface.

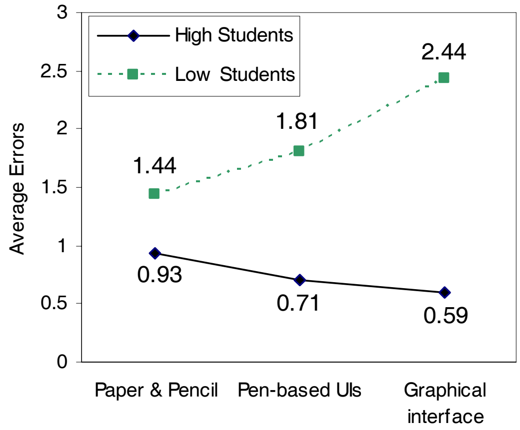


Figure 8. Difference between low- and high-performing students in math errors per condition as a function of pen-based (PP, DP) versus graphical tablet (GT) interfaces.

As predicted, students performed better when using a digital stylus and paper interface than pen or graphical tablet interfaces. From the viewpoint of Cognitive Load Theory, the digital stylus and paper interface enhanced performance best because it was most similar to students' existing hardcopy pencil and paper work practice. In particular, it incorporated pen input rather than a keyboard and mouse, and the familiar and tangible paper medium. It also was the simplest interface in terms of excluding extraneous interface "features," which were common in the tablet-based interfaces and distracted attention (e.g., different ink colors; lasso for encircling selected objects). Apart from these issues, the digital stylus and paper interfaces that span the physical and digital worlds offer a promising avenue for knowledge-gathering tasks in which users need to combine, cross-reference, and personalize information from different sources with pen-based annotations [15].

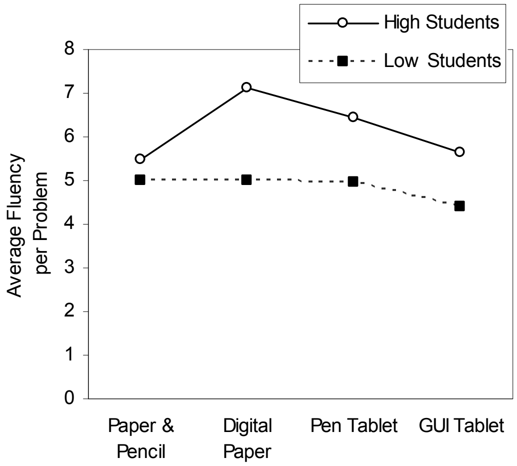
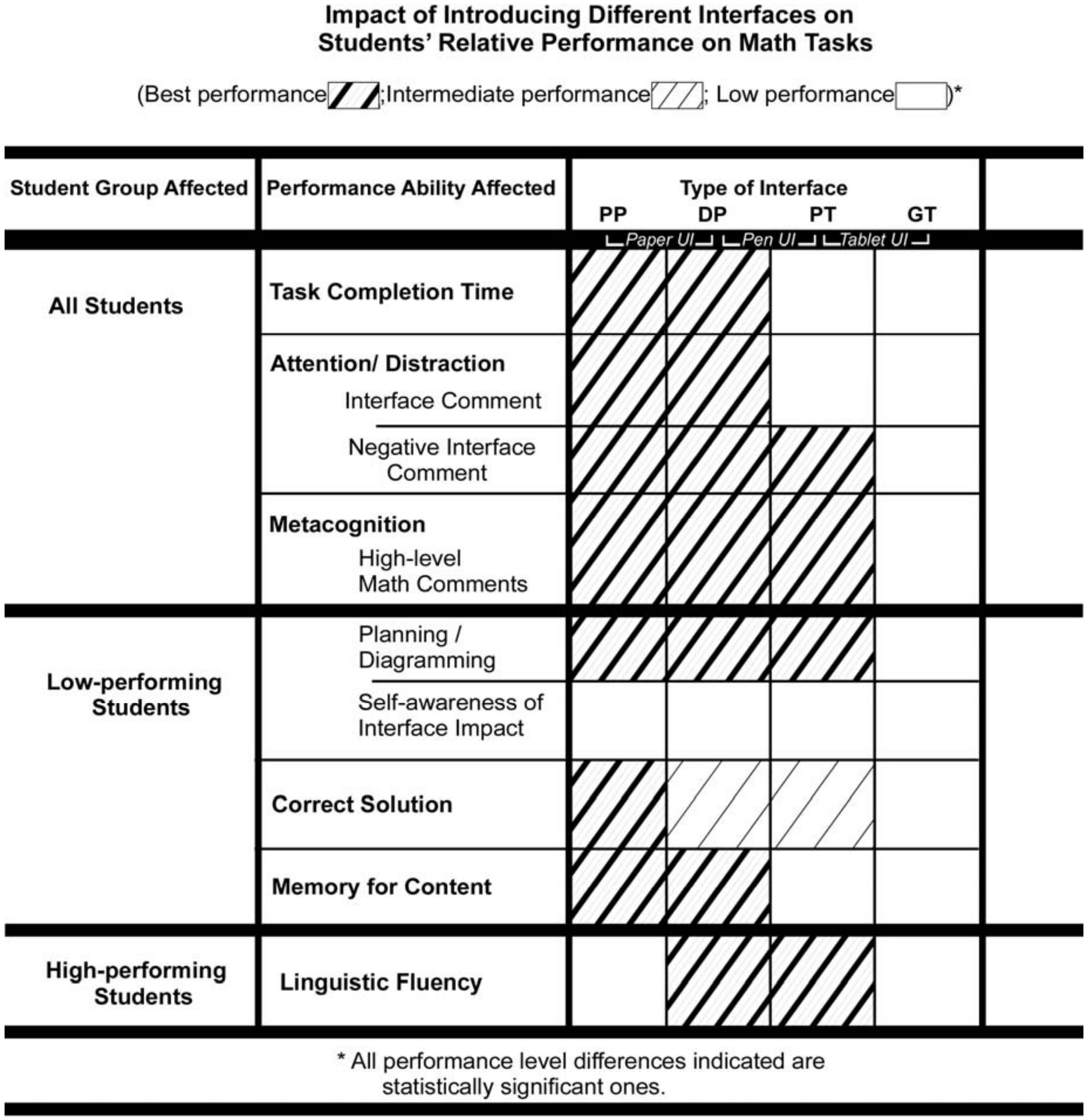


Figure 9. Overall fluency for low- versus high-performing students in different interface conditions.

In comparison, the pen tablet interface included the familiarity of a pen but not the paper medium, and the graphical interface least resembled students' existing work practice. Within the math domain, both of the pen-based interfaces (i.e., the digital paper and stylus, and pen tablet) also supported a broad range of expressive input in different representational systems, including linguistic, numeric, symbolic, and diagrammatic. As such, pen interfaces are particularly compatible with complex problem solving in domains like mathematics, which requires input fluency in all four representational systems and flexible translation among them. In contrast, whereas graphical interfaces provide good support for linguistic and numeric content, symbolic and diagrammatic input is poorly supported. Other attractive characteristics of the pen interfaces include their suitability for collaboration, mobility, and "bridging" of formal, informal, and mobile contexts [1, 3, 8, 14, 26, 32].



Impact of Introducing Different Interfaces on Students' Relative Performance on Math Tasks

(Best performance ▨; Intermediate performance ▧; Low performance ☐)*

Student Group Affected	Performance Ability Affected	Type of Interface			
		PP	DP	PT	GT
		└Paper UI┘	└Pen UI┘	└Tablet UI┘	
All Students	**Task Completion Time**	▨	▨	☐	☐
	Attention/ Distraction Interface Comment	▨	▨	☐	☐
	Negative Interface Comment	▨	▨	▨	☐
	Metacognition High-level Math Comments	▨	▨	▨	☐
Low-performing Students	Planning / Diagramming	▨	▨	▨	☐
	Self-awareness of Interface Impact	☐	☐	☐	☐
	Correct Solution	▨	▧	▧	☐
	Memory for Content	▨	▨	☐	☐
High-performing Students	**Linguistic Fluency**	☐	▨	▨	☐

* All performance level differences indicated are statistically significant ones.

Figure 10. Summary of the impact of different interfaces on specific cognitive skills as students completed math problem solving tasks.

In the future, it will be important that new interfaces for education, mobile computing, and other areas be designed to minimize cognitive load so users can focus on the intrinsic difficulty of performing well on their real-world tasks. One important issue uncovered by the present study is that low-performing students incurred a handicap when using the tablet interfaces, which higher-performing students simply did not experience. In the future, it will be especially important that educators participate in developing interfaces that minimize load in domains like math, especially for weaker students, in order to ensure that newly-introduced technologies do not create a *digital divide* that exacerbates rather than minimizing pre-existing performance differences between students.

With respect to the user-centered design principles outlined in Section 1.2, the results summarized in Figure 10 underscore that (1) *accommodating users' existing work practice*, rather than attempting to change it, yields substantial performance benefits. In addition, (2) *minimizing extraneous complexity due to unnecessary interface features* is associated with performance enhancement, as is (3) *minimizing the interruptions and distractions* that they generate, which can undermine users' focus of attention and ability to engage in high-level planning, integrative thinking, and problem solving. Finally, (4) *supporting representational systems needed by users to perform their task* facilitates performance. Regarding this latter point, traditional graphical interfaces still are surprisingly limited in the expressive power and breadth of input capabilities that they support.

4. CONCLUSION

At the beginning of this article we asked who is designing interfaces for Gilbert and the rest of us, who want to stay connected to the web of life while also using systems that help us focus and perform well. Human-centered design aims to build high-performance systems by acknowledging and modeling users' natural behavior, so interfaces can be designed that are more intuitive, easier to learn, and freer of performance errors. The potential impact of this approach is substantial improvement in the commercial viability of next-generation systems for a wide range of real-world applications. In this paper, we have illustrated different user-centered design principles and strategies, and their advantages and the manner in which they enhance users' performance. We also have summarized recent findings comparing the performance characteristics of new educational interface prototypes that were based on user-centered design principles. One theme throughout our discussion is that human-centered design which *minimizes users' cognitive load* can free up mental resources, permitting us to perform well while also remaining attuned to the world.

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