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Gaze-based HCI applications

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implications for type design and design's role in culture/technology conflicts

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Anticipating Gaze-Based HCI Applications with the Tech Receptivity Interval: Eye Tracking as Input

Matthew Peterson
Brad Tober
Deborah Littlejohn
Mac Hill

HCI researchers have repurposed diagnostic eye tracking technology as a mode of user input. Existing applications are numerous, but primarily address severe motor disability, with a recent increase in gaming enhancement. As noted by cognitive psychologist Nadiya Slobodenyuk, gaze-based HCI represents a fundamental change to the human–computer relationship if adopted for general interaction and information design purposes. A gaze-responsive system can make inferences on a user's mental state and respond rapidly without explicit user commands. The implications of such a system are significant, and are difficult to imagine and anticipate. We introduce the tech receptivity interval (TRI) as a framework to guide speculative design investigations that imagine potential applications of nascent technology. TRI distinguishes infancy and maturity conditions of receptivity, emphasizing the need for users to adapt to technologies before technological affordances can be fully realized. We provide case reports on gaze-based interaction, using TRI and conducted in an academic design studio. The case reports suggest applications not yet addressed in the literature. The case reports also suggest gaze-responsive changes to information structures in the form of temporal hierarchy and temporal text, which break from the long tradition of language representation in static lines and paragraphs.

Keywords –
diegetic prototypes,
embodied cognition,
extended mind,
gaze-controlled interfaces,
speculative design,
temporal hierarchy

Introduction

Psychologists have long observed the human gaze in laboratory settings, and the resultant decades of eye tracking studies have increasingly suggested an especially intimate eye–mind connection. Our predominant interaction with computers is presently manual; we issue overt commands through hand movements. If we outfit computers with gaze responsiveness we can issue qualitatively distinct and, in some cases, quantitatively more rapid commands. But given the nature of the eye–mind connection, a gaze-responsive system can also interpret inadvertent "tells" and unintentional actions in terms of desire or need, and respond to them as if they too were commands. An extreme realization of such a system raises the issue of technological invasiveness, as instantaneous inferences effectively defy the "skin-and-skull boundary," creating an extended mind (Buller, 2013). It is challenging to imagine such extensions to the mind *with a mind*, which must be done to consider the technology's promise.

We are here concerned with the promise of gaze-based HCI and use a conceptual framework and speculative design cases to explore that promise. We first address existing gaze-responsive issues and applications in a brief literature review. The literature on gaze-based HCI is necessarily limited by practical concerns: it is the most immediately achievable applications that have been explored directly in research and development. To anticipate gaze-responsive applications not yet suggested in the literature, we subsequently introduce the tech receptivity interval to structure a series of visual and interactive studies conducted by graduate students in design. The tech receptivity interval is a framework that guides speculative design for nascent technology. It emphasizes the relationship between human receptivity to technology and how humans change as they incrementally adapt to technology. Finally, we review the outcomes of the gaze-based interaction studies and what they suggest about the potential of gaze-responsive technology.

Previous Research on Gaze-Based Interaction

Researchers have long tracked eye movements in a *diagnostic* capacity; that is, to unobtrusively observe how people complete tasks such as scene perception, reading, and the navigation of interactive media by recording gaze patterns. Eye movements consist of fixations — moments of relatively fixed gaze — punctuated with saccades — quick movements from one fixation to the next. The gaze patterns provide insight into cognitive processing (Spoehr & Lehmkuhle, 1982): individual fixations and the gaze patterns they form in sequence offer information-rich opportunities for understanding human cognition. Fixations most directly indicate attention (Rayner, 2009). Recognizing the utility in a user's attention, researchers have explored how eye movements might be used in addition to or even in lieu of traditional input devices as a means of a user either intentionally communicating with a computer or unintentionally revealing desires and needs.

Duchowski (2002) distinguishes between eye tracking applications that are diagnostic and those that are *interactive*, i.e., where the user's gaze patterns change the display, noting that diagnostic represents the "mainstay" application. These diagnostic applications of eye tracking have occured in areas such as neuroscience, psychology, engineering, marketing, advertising, and computer science. While the most conspicuous examples of gaze-based interaction are in design for motor disability, a broader potential was imagined as early as the 1960s by Ivan Sutherland (1965). As digital technologies for diagnostic eye tracking applications have rapidly developed in more recent years, the feasibility of using those same technologies for interactive applications has increased as well. For instance, Tobii, a leading eye tracking technology company, was founded in 2001 to focus on diagnostic eye tracking applications, but has since expanded into the investigation of interactive applications as well ("The history of Tobii"). Furthermore, increased development of interactive eye tracking technologies has resulted in decreased cost, leading to the consideration of mass-market viability beyond specialized assistive applications. For example, prior to the company Eye Tribe's acquisition at the end of 2016, it sold its eye tracking hardware device for only $99 US (Constine, 2016). Along with this decreased cost and increased mass-market viability comes implications for the design and implementation of gaze-based interfaces.

Gaze-based interaction is worthy of exploration in part because it can significantly increase user-to-computer bandwidth, thus "redressing" a long-held discrepancy in human–computer communication (Jacob, 1991 & 1993). Adaptive user interfaces make use of increased user-to-computer bandwidth for user intent discrimination, inferring intent without demanding conscious gestures from users. The result is a more transparent system (Goldberg & Schryver, 1995). Transparency and intentionality are at the heart of gaze-based interaction. While the tap of a trackpad is an intentional act, gaze patterns are more automatic and more directly tied to concurrent interpretation. This direct connection does raise some issues. According to embodied cognition theory, which links the acting body to the mind, cognitive processes are directly influenced by bodily interaction with the environment, including eye movements (Slobodenyuk, 2015 & 2016). Thus investing eye movements with interface control could amount to interfering with the desirable cognitive processes that eye movements otherwise support. Given these issues, cognitive psychologist and HCI researcher Nadiya Slobodenyuk (2016) proposes a *cognitively grounded interface* based on gaze, which imbues an "intuitive sense of control" and proves "less likely to interfere with ongoing cognitive processes"; she notes that such work is as yet under-explored (p. 1035).

Early in gaze-based interaction research, Jacob (1993) determined that an interactive gaze system should favor natural over prescribed eye movements. *Natural* eye movements are those that occur unconsciously in regular scene inspection, while *prescribed* eye movements require conscious effort from the user. A natural interaction might, for instance, take the form of scanning a scene, where the user looks in a certain direction to see more in that area. The real world offers few such natural analogies between gaze and interface (pp. 5–6). The only major natural source of oculomotor agency is in the social context, where both other people and animals respond to our gaze (Slobodenyuk, 2016, p. 1039). In contrast, our sense of motor agency is well-established, which helps make the mouse and trackpad sensible as a means of control.

Table 1. Select recent applications of gaze-based interface.

Users or Domain	***Application***	***References***
Severe motor disability	Text entry, typing: utilizes a keyboard graphic. Relies on dwell time (slower) or algorithms that infer intent (rapid, more prone to false keystrokes).	(Bee & André, 2008; Kristensson & Vertanen, 2012; Liu, Lee, & McKeown, 2016; Pedrosa, Pimentel, & Truong, 2015)
	Text entry, gesturing: imbues gaze patterns with meaning.	(Bee & André, 2008)
		To assist in keystroke confirmation (Kurauchi et al., 2016)
		As writing system with learned system of gaze paths (Wobbrock et al., 2008)
	Text entry, continuous writing: gaze gestures utilized in patterns to indicate letters and words	Quickwriting (Bee & André, 2008) uses novel arrangement of letters in clusters. Passing through a cluster offers those letters in an outer ring, and the last letter contacted before the scan path returns to the center is selected.
		Dasher (Ward, Blackwell, & MacKay, 2002; Ward & MacKay, 2002) provides pathways towards selections based on the estimated probability for one letter following another. (Though difficult to describe, it feels like fluid travel through a sequence of spaces, each a letter in a growing set of words.)
	Drawing	(Hornof & Cavender, 2005)
	Web browsing	(Abe et al., 2008; Onishi et al., 2014)
	Drone control	(Hansen et al., 2014)
	Attentive user interface: recognizes user intention and uncertainty	(Prendinger et al., 2009)
Autism spectrum disorder (ASD)	Driving instruction	(Wade et al., 2016)
	Visual attention guidance	For adolescents with ASD (Wang et al., 2015)
Infants	Study of discovery of agency (despite poor motor control of infants, which usually inhibits such study)	(Wang et al., 2012)
Gaming	General interaction for rendering gameplay more immersive	Sundstedt (2012) provides an overview of gaze as "interaction device" in gaming; Isokoski et al. (2009) and Nacke et al. (2011) provide basic frameworks
	Gaze gestures for issuing commands (avoiding the need for players to look away from major action)	(Istance et al., 2010)
	Mimicking pupillary light reflex: ambient lighting of virtual environment is responsive to gaze point as in the natural world	("How to Play Assassin's Creed," n.d.)
	Mimicking social response: the original oculomotor form of agency, where people (here non-player characters) respond to the player's gaze as if sensitive to it	(Vidal et al., 2015)
Other	Large image inspection	(Adams, Witkowski, & Spence, 2008)
	Attention monitoring in tutoring	(D'Mello et al., 2012)
	Air traffic control	(Alonso et al., 2013)
General	Attentive user interface: an integrated system more "aware" of the user, only in part through gaze	Proposed by Vertegaal and Shell (2008)

Table 2. Gaze-based command techniques.

Selection Issue	***Technique***	***References***
General selection activation	Dwell: fixation duration before a selection is triggered; 400 milliseconds (ms) is general standard (Slobodenyuk, 2016)	Slobodenyuk (2016) provides overview; Jacob (1991) used 100, 400, 600 ms; Nayyar et al. (2017) developed adaptive algorithm to determine appropriate dwell times; Penkar, Lutteroth, and Weber (2012) related dwell time to selection target size
	Blink: eyes closed to a timed threshold	(Skovsgaard, Mateo, & Hansen, 2011; Évain et al., 2016)
	Multimodal: gaze supplemented with other input, such as mouse click	
Dynamically resizing and responsive activation areas	Bubble: a cursor that dynamically resizes its activation area depending on the proximity of surrounding targets	(Skovsgaard, Mateo, & Hansen, 2011)
	Lazy Bubble: a bubble cursor that resizes more slowly to reduce visual distraction	
	Cone Cursor: a cursor that displays a "tail" to the last enveloped target, always leaving a target selected	
Centering methods of proximity for gaze cursors	Force Field: a gradual attraction of the gaze cursor to the center of a gaze target (when in the area of the target)	(Skovsgaard, Mateo, & Hansen, 2011)
	Speed Reduction: when within the area of a gaze target, the gaze cursor moves more slowly	
	Warping Target: like a force field, but the gaze cursor immediately moves to the center of the gaze target once entering the target area	
Small target activation	Magnification: upon an initial activation, an enlarged version of the region pops up in a new overlapping window; typically a multi-step process	(Skovsgaard, Mateo, & Hansen, 2011)
	Zoom: a gradual increase in the size of the workspace (or a portion of it), as if approaching the user	
	Fish-Eye Lens: a localized zoom of targets (in display and motor space) around the point of the user's gaze	
Saccadic binding	Gaze Gesture: a learned pattern that issues a specific command	Hyrskykari, Istance, and Vickers (2012) note that the limitations of gaze gestures include their complexity and the need to incorporate a "means of reminding the user of what [particular command-gesture mappings] are without disturbing the gesture, which is not a trivial design problem" (p. 229)

While many gaze-responsive applications address severe motor disability (e.g., Bee & André, 2008), others consider the affordances of gaze for enriching or extending human–computer interaction. Table 1 lists a range of recent gaze-based applications. These applications — from fluid writing for those with motor disabilities (Ward, Blackwell, & MacKay 2002; Ward & MacKay, 2002) to increasing immersion for gamers (Sundstedt, 2012) — have served collectively as a test bed for the development of general techniques. Techniques related to issuing basic commands have necessarily been explored in some depth, with some examples provided in Table 2. A pervasive complication for selection in a gaze-based interface is the *Midas touch problem* (Jacob, 1991), which refers to the likely confusion and frustration a user experiences in a display with too many gaze-sensitive zones, which is likely to register inadvertent commands. While this fundamental issue has been mitigated in recent design solutions (Slobodenyuk, 2016, pp. 1036–1037), it is likely to remain an obstacle for emerging innovations in gaze-based interaction that seek to construct systems that feel more automatic in their responses to a user's visual exploration of information-rich interfaces.

Slobodenyuk (2016) notes that the location of gaze-control buttons and the choreography of gaze patterns should be subject to *stimulus–gaze response compatibility*: the matching of a response type to one or more stimulus properties. In a non-gaze example of stimulus–response compatibility, a keyboard-based interaction that pairs hitting a right-hand key with a beep heard in the right ear is a more compatible response than left hand to right ear. Slobodenyuk describes the size of the "gaze control zone" — a two-dimensional area that will trigger a response if focused on directly — and the presence of a gaze cursor — a "visual indication of the point of gaze" — as spatial components that may be used in reinforcing this stimulus–gaze response compatibility (p. 1040). Careful coordination can give the user a strong sense of agency. However, spatial considerations are not limited to singular discrete fixations. Spatial clusters of attention, or multiple fixations in one small area of a display, indicate user attention and can suggest more about user intent than scan paths alone (Goldberg & Schryver, 1995).

The affordances of cognitively-grounded gaze-based interaction are multitudinous, surely with implications and possibilities well beyond what has been discussed in the literature to date. The imagined and realized applications listed in Table 1 are more immediate and tend not to address the fundamental question of how the nature of the human–computer relationship might evolve when the latter can sense more from the former — when, for example, the human is not just communicating intent but is evidencing attention, interest, arousal, confusion, and myriad other states of mind. This raises a host of questions. How might the very nature of information hierarchy change when a system can selectively provide a user with more information at the current gaze point, without the need for visual searching? How might the very paradigm of reading change when reading systems can serve information to a reader instead of the traditional provision of a surface to be explored through the patterned scanning of lines of type? Such questions suggest the depth of potential investigations that have yet to be undertaken, if indeed gaze-based interface holds the promise that Slobodenyuk (2016) imagines: a "natural and effortless experience of self-agency" (p. 1037).

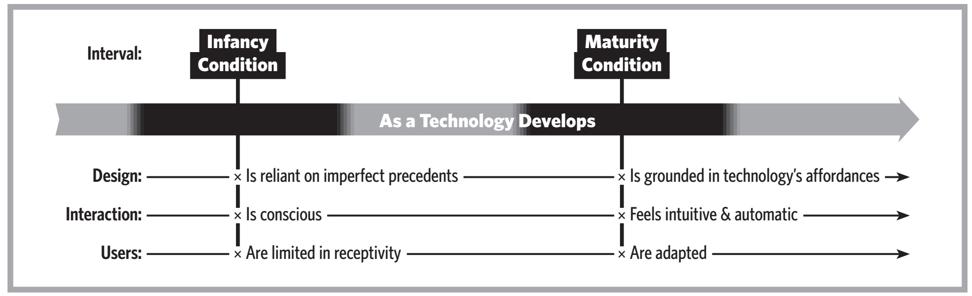
Tech Receptivity Interval

The most intimate applications of gaze-based interaction, where a smart system fluidly modifies information presentation based on dynamic user mental states, challenges the notion of a "skin-and-skull boundary" between human and computer (Buller, 2013), despite the absence of a physical brain–machine interface. Clark and Chalmers (1998) describe any coupled interactive system, where a human's behavioral competence is dependent upon an external entity, as *active externalism*. The corresponding *extended mind* premise equates integrated environmental processes (e.g., the actions of a gaze-responsive system) with internal processes (i.e., cognition). Clark (2007) describes adaptation within such integrated systems, with examples of muscle–machine and brain–machine interfaces where the organism (human and monkey, respectively) ultimately operates without conscious thought. We assume that the adaptation process in relation to an integrated gaze-based interaction system will largely mirror these physical examples, and that users will, according to Clark's terminology, "calibrate" themselves to the technology and gain a sense of that technology's "transparency" (p. 274), or more accurately lose the conscious sense of its presence. Cognitive agents (e.g.,

humans) are not consciously aware of many of their own cognitive operations (p. 274), which poses a problem in anticipating the use of a technology as intimate as we expect gaze-based interface to be: designers must speculate on user experience when that experience would not altogether be explicit even to the user. *Cognitive phenomenology* refers to the "thinking of thoughts" in contrast to conscious awareness of sensations like pain (Walsh, 2017, pp. 34–35). The cognitive phenomenology of gaze-based interaction is integral to the technology's potential and realization.

FIGURE 1

Tech receptivity interval.



To speculate on as-yet-unrealized applications of gaze-based interaction, we have adopted Kirby's (2010) *diegetic prototyping,* which considers future technology in a naturalistic way, with requisite environmental changes to enable its use (pp. 43–44). We present a simple framework, the tech receptivity interval, to help designers produce diegetic prototypes that are as sensitive as possible to the cognitive phenomenology of a relatively transparent technology (Figure 1). The *tech receptivity interval* (TRI) foregrounds user response to technology by focusing attention on how the user recalibrates herself with its use. This focus on the user distinguishes it from an earlier framework by Ulhøi and Gattiker (2000) on technological paradigms and trajectories, which views technological development and innovation from an organizational perspective — not a user perspective. TRI is bounded on one end by the *infancy condition,* a point where a technology is new and users are unfamiliar with it. Under this condition, users are likely to approach the technology with imperfect precedents in mind and operate under assumptions tied to those analogs. For instance, the earliest web design was made to appear remarkably similar to print, a format of information presentation to which users had previously adapted and to which they were presumably more receptive. On the other end of the interval is the *maturity condition,* where users have had time to adapt to a technology, and where that technology can be presented and experienced in a way that best aligns with its own affordances, and not those of dissimilar precedents. The maturity condition represents a state where the technology's application has developed iteratively, each iteration dependent upon increased human adaptation, with correspondingly increased receptivity.

Gaze-activated image inspection offers an example for infancy–maturity distinctions. In an infancy condition, a user might look at an image of interest on screen, and following a specified duration be provided a zoom icon, which triggers an image inspection mode upon fixation. In a more mature condition, the user might look at an image and tighten the muscles around her eyes in a subtle squint, which fluidly triggers the image's growth in a full screen inspection mode. A deep blink could then suggest interest has waned and trigger the image to zoom back out, with the screen returning to its previous display. The latter example would be more fluid and feel more responsive to the user, but it is more dependent upon human adaptation.

TRI renders its two anchor conditions explicit for designers involved in diegetic prototyping, thereby encouraging designers to consider both conditions within extended design exploration, producing contrasting studies based on human–technology relationships. We believe this helps ground the designer's exploration by not simply imagining a fantastical future, but rather by consciously considering bounded human and technological limitations. But TRI is not a panacea. Such exploration is still dependent upon the designer's imagination as modulated by a design process, which is an unavoidable limitation. TRI is further limited by the designer's ability to anticipate a future user's phenomenological sense of the technology in question. Given the intrinsic challenge of designing for a phenomenologically transparent technology that cannot yet be experienced directly by designers, rooting scenarios in the familiar social context of the present — rather than an unfamiliar future — limits the variables that must be considered. TRI thus can fix the present to foreground the contrast between user receptivity and adaptation to technology in states more and less familiar. TRI is concerned with the naturalization of a particular technology and not immersive science fiction that aims to present a fully-fledged world. Imagining alternate present states — one where a technology's reception is infantile and another where it is mature — is intended to avoid what the first and third authors have experienced as "magic" in student work. Magic design occurs when students attempt to sidestep technological challenges by assuming that all potential dependent technologies will develop to make anything possible. The following cases relied on TRI as a framework for investigation in an alternate present states scenario.

Gaze-Based Interaction Cases

Prototyping as Inquiry

The development of technology is not "inevitable, predestined or linear" (Kirby, 2010, p. 44), and thus case reports that suggest the promise of gaze-based interaction can serve to guide the development of the eye tracking software, hardware, and practices upon which their ultimate realization depends. Researchers in the visual design fields have an opportunity to make significant contributions in the development of technology due to the skills designers attain not only in lateral thinking, but in speculative imagining. (Though speculative design is frequently discussed in terms of criticism and what *should* and *should not be* [Dunne & Raby, 2013; Mitrović & Šuran, 2016; Kirby, 2010], we are presently limiting our interest to initial speculation on what *could be* [Slobodenyuk, 2016, p. 1045].) In their proposal for a model of design as an HCI research method, Zimmerman, Forlizzi, and Evenson (2007) argue that HCI has a great deal to benefit from the perspective of design's holistic approach to addressing

low-constraint, wicked problems. In early collaborations with HCI and software developers, designers were involved only at the end of project timelines for the beautification of interfaces. Increasingly designers are involved in the development cycle (p. 4).

Speculation in design concerns two overarching themes: imagining possible or plausible futures (Dunne & Raby, 2013) and designing an alternate present, which refers to the creation of congruent realities. Speculative design practice envisions not only alternate products and systems, but also alternate worlds (Mitrović, 2016, p. 7). In this mode, designers reimagine the role of technology in current everyday life without having to confront the actual application of the technology or its constraints. Rather, they are free to consider implications and possibilities. The designer uses design as a medium and focuses on concepts and artifacts and, rather than solving problems, asks questions and opens up topics for debate. As a speculative enterprise, the act of designing is a mode of inquiry, where the creative process materializes alternate futures through the creation of not only physical prototypes of artifacts, but prototypes of ideas.

By creating prototypes of ideas in a material form, questions about a technology, its possible uses, or its characteristics, can be revealed in a concrete way. Furthermore, prototypes are a means of communicating ideas to others, especially within a collaborative multidisciplinary research setting, with an aim towards facilitating meaningful conversation and making group decisions. Speculative prototypes promote dialogue among engineers, designers, and potential users (Mitrović, 2016, p. 7). Similarly, diegetic prototypes of technology in film help audiences see benefits before the technology is available to them (Kirby, 2010), and prototypes not only in film but in other forms of discourse performatively demonstrate "technologies-in-the-making" (Suchman, Trigg, & Blomberg, 2002, p. 164).

Guiding Design Exploration According to TRI

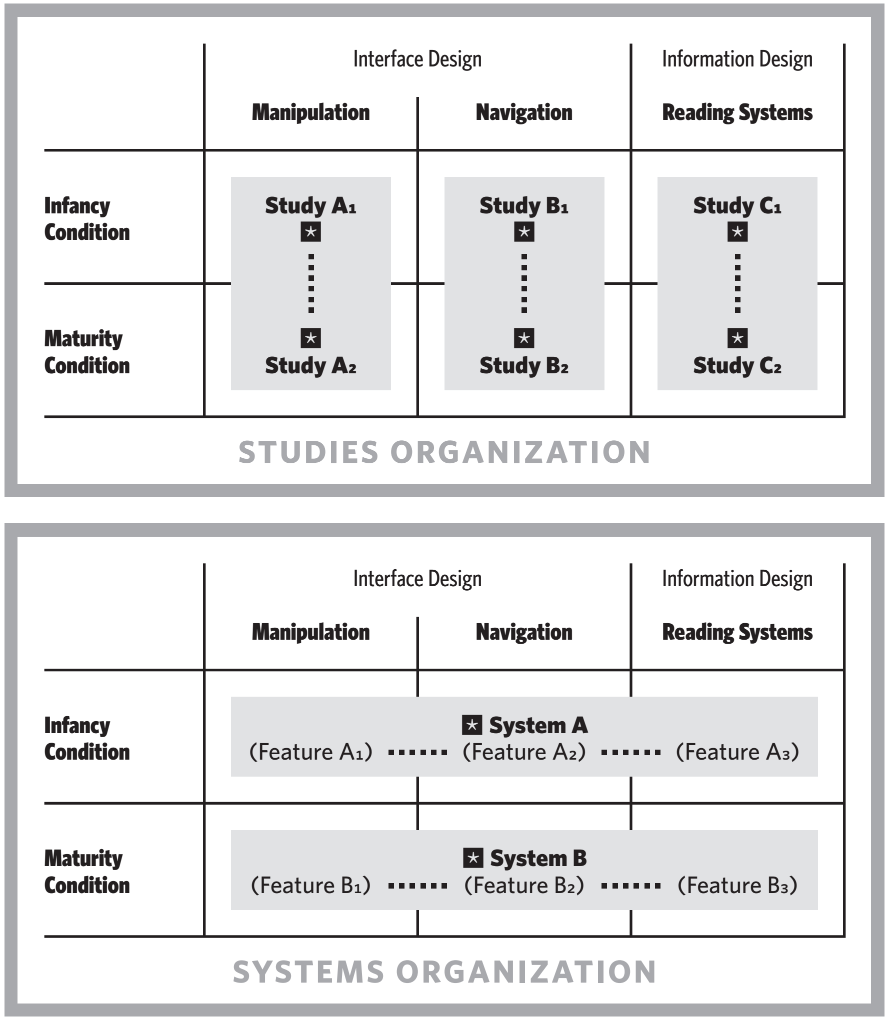
As Slobodenyuk (2016) suggests, "there is certainly space for aspiration that if the issue of cognition embodied in eye movements is addressed in gaze-controlled interfaces, the resulting coupling of the user and interface could be not only as good as, but non-superficially superior to hand-based interface interaction" (p. 1045). It was in that aspirational sense that we leveraged design's inherent ability to imagine possibilities for "what could be" (p. 1045), and thus to broaden our understanding of the potential of gaze-based interaction, with a guided series of design investigations in a graduate-level design studio at a public research university in the United States. The first and third authors were instructors for the course, the second author conducted an embedded workshop, and the fourth author was one of seven student participants.

The tech receptivity interval (TRI) guided investigations and emphasized the importance of human adaptation for more advanced applications of gaze-based interaction. There were three phases of student exploration:

1. Studies (four weeks, concurrent with other unrelated deliverables)
2. Visitor's workshop (one weekend, Friday–Monday, during the studies period), which did not explicitly utilize TRI
3. Systems (two weeks)

FIGURE 2

Investigation framework for studies and systems.
Studies explored both conditions (i.e., infancy, maturity) in one interactive opportunity (e.g., manipulation), while systems explored one condition across all interactive opportunities. (A separate workshop did not utilize this framework.)



Studies and systems required students to define their own topics or problems, while the visitor's workshop identified its topic in the project brief. Studies and systems were defined according to a framework shown in Figure 2. To ensure that students explored a wide range of potential applications, *interactive opportunities* were categorized as one of two interface design opportunities, (a) the manipulation of elements (e.g., dragging a link to save it) or (b) navigation, or an information design opportunity, (c) reading systems (e.g., text presentation structures). *Studies* were rapidly prototyped, rendered in lower visual fidelity, and were focused on addressing only one of the three interactive opportunity categories (i.e., columns in Figure 2). However, studies had to be conducted in pairs, with one imagining the technology in an infancy condition according to TRI and the other in a maturity condition, where well-adapted users would make more imaginative applications possible. By working across these conditions simultaneously in paired studies, the designers had to address human adaptation to technology directly. Subsequent *systems* were explored under one TRI condition (i.e., rows in Figure 2) that addressed all three interactive opportunities in higher fidelity and with extended narrative presentation.

The project brief introduced a scenario with TRI as follows: *In the maturity condition, gaze-based interaction is at present an established technology, and users have an established sense of oculomotor agency in HCI.* The scenario imagined a past where the light pen, featured in Ivan Sutherland's famous 1963 Sketchpad demo (M. Saleh KAYYALI, 2012), led directly to Douglas Engelbart's use of eye tracking in his "Mother of All Demos" (MarcelVEVO, 2012), and not a mouse, as actually occurred. An alternate present for TRI was favored over a near future because this stance kept the designers operating within their understanding of the contemporary context (excepting only that eye tracking was assumed to be more advanced), instead of possibly relying on undefined contexts to retroactively justify ideas that were not otherwise viable. The infancy condition was effectively the actual present.

TRI's use was thus relatively simple: it provided a structure for differentiating studies and ultimately selecting a system to pursue in more detail. However, in an exploratory design process, where the designer is making thousands of tiny decisions, only a simple framework avoids overt interference. Given this use, we consider TRI to be a special type of conceptual framework. Conceptual frameworks typically "categorize and describe concepts relevant to [a] study" (Rocco & Plakhotnik, 2009, p. 122). In objectivist research they organize literature before data is collected, while in subjectivist research they are often developed in the course of study (Varpio et al., 2019). For our more pragmatic investigation through design, we consider TRI to be an *investigation framework,* which serves not to describe reality but as a guide to ideation. More particularly for our use, the goal with TRI was to keep human adaptation to technology in the designers' minds as they worked.

Informing Design Exploration with Technological Experiences

The visitor's workshop addressed the inherent challenge in imagining a phenomenologically direct form of interaction where the interface is an extension of the user's mind. To realize the sort of speculative imagining described previously, not only must the technological tools enabling such activity exist, but they must also be accessible by those wishing to engage in such activity. While eye tracking technologies facilitating the development of gaze-based interfaces do indeed exist, the highly specialized technical knowledge necessary to leverage most of these technologies is daunting for many, designers included. To that end, we introduce GazeKit, a web-browser-based framework of HTML, CSS, and JavaScript that facilitates the prototyping of gaze-based interface designs. GazeKit integrates a number of existing JavaScript libraries to make this possible, including WebGazer, which utilizes common webcams for eye tracking in real time (Papoutsaki et al., 2016).

There are a number of advantages to using WebGazer, including the ability to leverage the democratizing force that it represents: it only requires a regular webcam to perform eye tracking tasks rather than specific eye tracking hardware. There is thus a pre-existing user base. Another advantage is the ease with which WebGazer integrates with web-based technologies that are already familiar to many designers. However, it has in our experience a frustratingly low accuracy in relation to other eye tracking options, which is a disadvantage. Gaze data from the Eye Tribe low-cost eye tracking hardware has been successfully integrated into the GazeKit framework, while the location of the computer's mouse cursor can also be used as a surrogate for gaze coordinates in testing.

GazeKit uses a system of views and targets to prototype a gaze-based interface design. This works very similarly to other conventional prototyping tools like InVision, where individual interface mockup views are linked via the placement of clickable or tappable hotspots. In GazeKit, every visual change to the interface is represented as a separate view, even when changes appear to occur within one view. Targets are specified regions of the screen where a gaze fixation of a specified dwell time will execute a task. GazeKit implements four types of targets: rectangle and circle targets, and negative versions of each. The negative targets activate the entirety of the screen except for the area specified — this type of target is useful in implementing multiple-step activation processes, for example.

The second author, who developed GazeKit, facilitated an intensive four-day workshop wherein students created and experienced basic gaze-based interfaces through hands-on exposure to the eye tracking technology. The workshop was a self-contained exploration of a gaze-based Wikipedia redesign parallel to students' self-guided consideration of TRI. Students used GazeKit to develop a gaze-based interface design response that either embraced or attempted to remediate "the problem with Wikipedia," which is the tendency of readers to get lost in "rabbit holes" (Munroe, 2007). This topic was used solely in the context of the workshop with GazeKit. While the workshop was constrained in scope, it was meant to provide direct experiences for students to build on as they speculated in their studies and systems. GazeKit is necessarily limited as an early-stage prototyping tool, but it represents access for designers to, and promotes the development of tacit knowledge regarding, a potential paradigm shift in HCI. Even if gaze-based interaction does not prove to be a paradigm shift, tools like GazeKit can help to make that determination by enriching speculative investigation.

Case Reports

Working within the initial investigation framework, participating designers developed a varied range of speculations about the potential of gaze-based interface design in both infancy and maturity conditions (see Peterson et al., 2017, for summaries and mock-ups). Designers explored reading systems in a variety of possible contexts, suggesting that the design of a

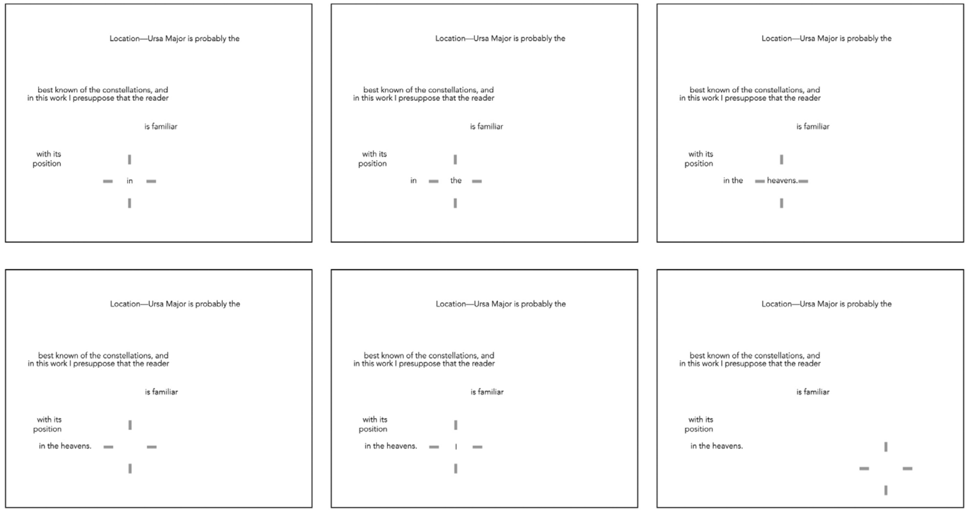
gaze-responsive reading system could have wide-ranging impacts on interface design. One set of studies used gaze as an indicator of focus level to generate textual interfaces that account for skimming and searching behaviors (Figure 3). In the infancy condition, a user's unfocused or erratic gaze causes text to drop out or disappear to accommodate skimming, or "tracks reading patterns to keep readers alert," while in the maturity condition the interface restructures future content to accommodate the user's unfocused state in an attempt to secure the user's focus (Nedić, 2017). This is a case of a smart system making an inference about user intent and adjusting information display to accommodate the intended behavior. Other projects incorporated pre-existing alternatives to traditional paragraph layouts to establish new reading formats in the infancy condition, such as the incorporation of rapid serial visual presentation techniques (where text is presented one word at a time in a single fixation zone), or kinetic typographic layouts that use gaze to designate the placement of text (where text follows gaze instead of the common alternative) (Figure 4).

FIGURE 3

Text layout adjusting to skimming behaviors.
Using a research application as the context of use, the designer investigated how text layout changes in response to gaze behaviors. The interface uses the reader's gaze input to detect skimming or searching behaviors and adjusts the text so relevant words appear larger and change color. This feature assists the reader in moving through a text quickly, while noticeable changes in the layout encourage reflection on wavering attention levels. Design by Dajana Nedić.

F I G U R E 4

Gaze-controlled text layout.
RSVP technology in a gaze-based interface allows a reader to dictate the placement of text on a page, creating a unique record of the reading experience that functions "like concrete poetry." Design by Mac Hill.



Other investigations addressed the reflective possibilities of gaze beyond a reading context. Designers explored gaze patterns related to user attention and comprehension in varied activities (e.g., viewing a lecture, completing educational exercises) that alert the system when immediate and personalized feedback is required. Gaze features like this, when integrated into an online learning environment, could provide students with more individualized learning aids through additional feedback and reflective tools not available in contemporary gesture and mouse-driven environments (Figure 5). Designing for both infancy and maturity conditions, these studies considered how gaze-based technology would change the way a student interacts with an online learning platform, specifically one teaching art history, both by tracking the student's attention to material (infancy condition) and providing feedback based on the student's gaze input (maturity condition) (Bordas, 2017).

F I G U R E 5 f o l l o w i n g p a g e

Reflective gaze features in an e-learning platform.
When a user's gaze is not following a lecture or lesson closely, or exhibits patterns that suggest user inattentiveness, the system provides feedback through a score, which in turn, encourages personal reflection. The system also adds a secondary gaze layer as an optional marker of the professor's gaze, pre-recorded and mapped onto the presented content to "help the student maintain… her attention and keep track of the course [material]." The professor's gaze acts as a kind of highlight for students to see where they should be focused, or, if not, becomes a prompt for students to reflect on why they are missing information. Design by Clément Bordas.

Designers also explored how a user's gaze could create a record of a navigational path through an application, in both academic research and internet browsing contexts. Studies utilized a user's dwell time on specific terms or other elements on screen as indicators of direct interest or personal significance (infancy condition), and paired those findings with a system that adjusts the interface accordingly (maturity condition), either with structures resembling concept maps or by customizing the hierarchy of the page (Figures 6 and 7).

FIGURE 6

Using dwell time to create maps of reading.
In this study, dwell time and behavior mark keywords on a page, collecting them in a concept map structure that shows a user's path through an article or website, in this case a Wikipedia article. This concept map becomes a residual artifact of the user's reading process, which can be revisited to reveal connections between otherwise disparate moments. Design by Dajana Nedić.

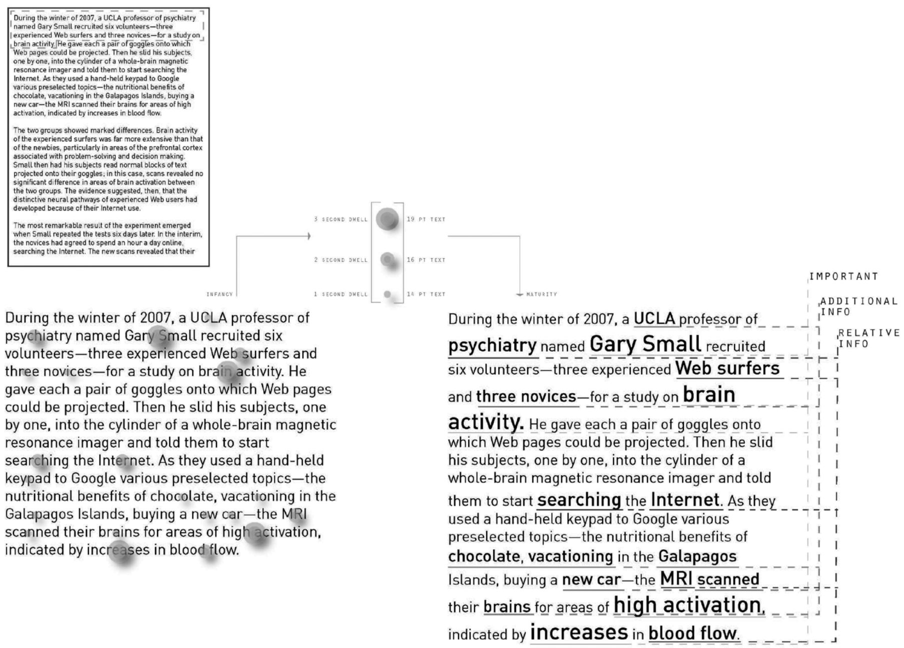
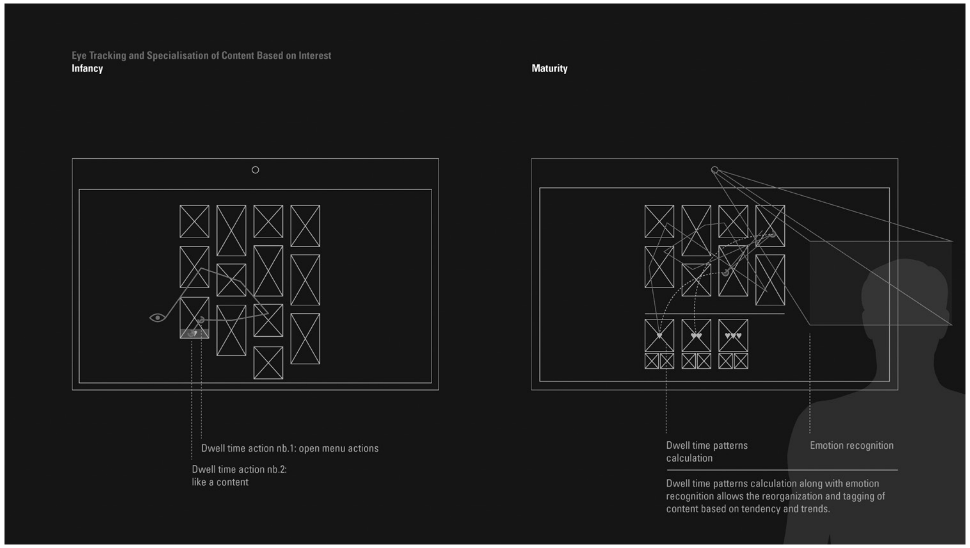


FIGURE 7

Gaze-determined page hierarchy.
A customized hierarchy reflects user interest, as interpreted from fixations and other gaze behaviors. An interface like Pinterest creates categories and reorganizes based on a user's gaze inputs, rather than entered categories or "pins." The designer envisioned this futures-oriented gaze-based interface as being supported by machine learning "to enhance and maximize the time we usually spend on the research of content." Design by Clément Bordas.



For the system exploration, one designer explored how gaze could be used for quick gestures. By interrogating the relationship between orientational metaphor (e.g., an orientational "up is good" metaphor to structure further conceptualizations) and visual processing, the designer developed a metaphorically grounded system based on the four cardinal directions, which are activated by fixations at the edges of a screen (Figure 8) (Lakoff & Johnson, 1980; Gentner, 2001; Frith, 1996; Vetter, Smith, & Muckli, 2014). This spatial framework permits a user to navigate hands-free through a music streaming interface. The designer's framework pairs existing spatial reasoning with gaze, creating stimulus–response compatibility, suggesting that the associated actions would be more intuitive. The designer posited that this four quadrant spatial model could apply to numerous gaze-based interfaces beyond music applications.

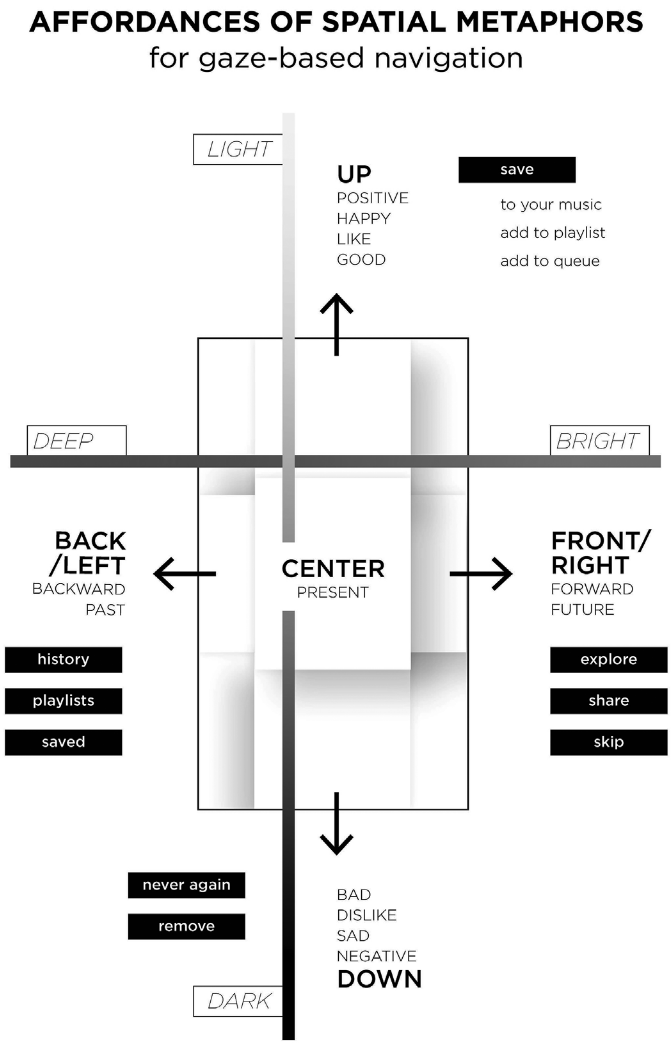


FIGURE 8

Spatial metaphors in a gaze-based music application.
The designer's four quadrant system pairs the cardinal directions and their associated spatial metaphors with the various actions of the interface. In the system, up is associated with a positive experience, down with negative, right (or front) with the future, and left (or back) with the past. These directions are associated with the actions of the interface that align to the aforementioned metaphors. For example, up is paired with saving a song to a user library and down is paired with removing a song or blocking the interface from playing it again. Design by Rachael Paine.

When speculating about gaze-responsiveness in a maturity condition, designers wondered how an interface could react to multiple gaze inputs, in public as well as with large scale displays. Designers offered solutions ranging from an interface that could act "democratically," displaying information based on where the most concurrent fixations fell, to one that divides

and offers distinct displays based on multiple gazes. In both scenarios users "are 'battling' for what information will be displayed" (McMahon, 2017).

The framework laid out for these gaze explorations allowed designers to iterate quickly and explore numerous contexts and problem spaces. In the infancy condition, designers speculated on reading, reflection, and how orientational metaphors can influence a gaze interface, as well as the basic implications of gaze in decontextualized situations. One study examined how a user would navigate complex layers of information or material with gaze alone, while another addressed navigation between text and image and the affordances gaze would bring to reading experiences. The maturity condition pushed designers to combine gaze with other technologies, speculating on future solutions to complex issues. One designer imagined the use of pitch (i.e., sound) in concert with gaze patterns for users with low vision. While another designer saw gaze as a diagnostic tool for testing customized content tailored to user behavior. The designers' investigations were far from comprehensive, but rather represented an expanded application space suggested by the affordances of gaze-based interface. This kind of individually-motivated exploration can suggest contexts (e.g., public spaces, online lecture courses) with stakeholders (e.g., instructors, students) who would be unlikely to consider the potential of gaze-based interface, but whose tasks may be greatly enriched by it.

Discussion

Approaching Gaze-Based Interaction

Gaze-based interaction is a rich problem space that will benefit from the kind of lateral thinking and speculative imagining associated with design and designers. The case reports provided here occurred in academia. This context is an ideal place for the speculative work that is required, with its mandate for futures-oriented inquiry and the motivated and intellectual contribution of students. However, as long as the idea of gaze-based interface is compelling, design novices and experts alike, in organizations or in virtual communities, can contribute to imagining a new future in HCI — or better yet, a plausible new present.

The student investigations detailed here offer several suggestions for potential gaze-responsive systems, well beyond the applications covered in the literature review. The literature, rooted in the infancy condition of our actual present, is rightly preoccupied with navigational selection. Selection is indeed problematic in a gaze-responsive system, and it is tied to the core issue of intentionality. How can a system that is provisionally able to infer intent instead of merely awaiting an explicit user command, enhance agency rather than threaten it? Of special interest in a more speculative mode, and for a plausible future's maturity condition, are gaze implications for both information hierarchy and textual structure. In the designers' explorations, gaze responsiveness often equated with dynamic reconfigurations at the gaze point, where hierarchy and textual structure are organized in time rather than in space. These central themes of temporal hierarchy and temporal text emerged in a series of design critiques, where students informally sought patterns among their studies and systems. We will discuss these themes momentarily, but first we acknowledge some limitations that emerged from the design investigations.

As is evident in the case reports, the openness of the assignment in concert with the minimal interference of TRI resulted in a great diversity of possibilities. This diversity is somewhat overwhelming. TRI moderated design production, but it does not serve as an evaluative tool. In retrospect, we believe the classwide investigation would collectively better function as an exploratory phase to a subsequent targeted phase with a more limited application space. However, even were there more time available in this particular case, that subsequent phase would function best with a more advanced eye tracking system than was available to us, and which may well not have existed for true gaze responsiveness at the time. The separation of visual fidelity (in the studies and systems) from interactive fidelity (in the workshop) was appropriate and even necessary, but it is a severe limitation to deeper exploration.

Temporal Hierarchy

In virtually all media, hierarchy remains a matter of the arrangement of elements on a two-dimensional surface that a reader then navigates with her gaze, taking cues and relying on conventions. Large text is read as hierarchically "higher" than small text. Any reasonably complex informational surface is rapidly traversed by its reader, whose initial fixations give her the "gist of the scene" (Carroll, Young, & Guertin, 1992), while she picks up on visual cues and builds a model of that surface's information hierarchy. This guides her subsequent decisions on where to attend. It is important to note that this establishing "gist phase" is a matter of gaze patterns. System responsiveness to fixation points has the potential to destabilize our very notion of hierarchy.

Though conventional hierarchical arrangements are distributions on a two-dimensional surface, the elements are experienced temporally. A gaze-responsive system could feature temporal hierarchy, where "lower hierarchy" elements follow "higher" ones in a single fixation zone. As such, elements become hierarchically immediate (née higher) and subsequent (née lower). How much more rapid might temporal hierarchy make inspection and navigation? Perhaps more importantly, how might it make a user feel? It is exceedingly difficult to imagine such interaction because it represents a foundational change in information display. Consideration of infancy and maturity conditions is useful because it keeps the speculative designer honest about how certain unconventional interaction modifications might prove disorienting to users (in infancy) until transitional scaffolds have been put in place.

Temporal Text

In Western writing, the word space emerged in the seventh century, after display in lines and columns was long established (Saenger, 1997). The later division of prose into discrete paragraphs followed the invention of the printing press (Bringhurst, 2008). No major revisions beyond the structure of word to line to column to paragraph have made their way into the everyday reading experience, despite the computer's ubiquity — except, perhaps, for those who currently utilize rapid serial visual presentation (RSVP) technology. Conventional Western reading arranges words left-to-right in lines, which are themselves arranged top-to-bottom. The reader tracks her gaze through this pattern. In expert reading, ideal fixation points are found internal to most words and saccadic jumps from line-to-line are accurate (especially when aided by expert typography). RSVP reverses the relationship and effectively brings words to the reader, displaying them one at a time, in rapid succession, in a single fixation zone. Spritz (n.d.) in particular determines each word's ideal fixation point and highlights that letter in red, with word placement aligned to that red letter such that all red letters appear in

the same location with word alignment following, shifting slightly side to side. Furthermore, in Spritz as in other RSVP applications, the pacing of words is not constant but is relative to word length and complexity. Users can adjust the overall reading speed, and if you use RSVP you will find that you can manage a faster rate with practice.

RSVP is largely framed as a speed-reading technology. It also has obvious efficacy for screens of limited size where space-dependent conventional prose structures cannot be accommodated. But RSVP, as considered in the context of a gaze-responsive system, represents a profound change in the nature of language presentation — greater than any of the incremental historical innovations of word space, line, column, and paragraph. It is an interesting question alone of how continued RSVP use might alter our relationship to text. We would need a new name for such textual structure, as neither *prose* nor *verse* is accurate. In an integrated gaze-responsive system, entire texts could be collapsed into their respective areas, available simultaneously on one screen. Instead of an aggregation page collecting links to separate articles, a system with RSVP might give the user access to texts themselves at the point of "gaze inquiry," a fixation with its inherent implication of interest. As with temporal hierarchy, temporal text suggests a surfeit of possibilities, each with implications for how we relate to information itself.

Conclusion

The tech receptivity interval (TRI) conceptualizes technology in terms of human adaptation to it, and emphasizes the dependence of technology on its reception. TRI was used to guide speculative design investigations in a design studio, some of which we introduced here. While these investigations forward myriad possibilities of gaze-based interface, their variety suggests that there are likely many more unexplored applications. The gaze-based HCI literature alone outlines many useful applications. The literature, in which practical applications predominate, represents an ongoing exploration of an infancy condition in gaze-based interface adoption. Speculative design prototyping can expand the concerns of the literature by looking forward to more advanced applications in a maturity condition.

The phenomenology of mature gaze-based interaction, where the gaze-responsive system functions as an extended mind, is not just difficult to imagine, but it is quite likely to be ethically fraught. Brain–machine interfaces, such as the cochlear implant (Lee, 2016), raise issues of invasiveness (Buller, 2013), autonomy, and identity (Lee, 2016). The extended mind premise suggests that intimate gaze-based interaction is subject to the same issues. While we have not addressed these issues here, they should not be ignored as exploratory ideation transitions into considered application.

Upon acceptance of the foundational shift that gaze-based interaction brings to issues such as hierarchy and text display, an HCI rabbit hole appears to open up. Any of the areas of interface and information design isolated in the design studio prompt — of manipulation, navigation, and reading systems — includes conventional structures that implicitly assume no gaze responsiveness. Such conventional structures might be stripped away in a gaze-based interface. For example, within reading systems, the table represents an opportunity for investigation. Tables use alignments to sort and relate information. How might a gaze-responsive system release information to a reader in a manner that functions like a table but looks nothing like it, reconfiguring itself on the fly? Questions like this one require a deconstruction of conventional information structures, divorcing function from presentation-dependent features and then applying that function to another format. There are surely additional functions that a gaze-responsive system can accommodate that have no existing corollary, which are unlikely to occur to us before or even within an infancy period of the technology's adoption. Continued investigation is needed to determine if Slobodenyuk's (2016) aspiration for gaze's efficacy is to be fulfilled: that beyond existing assistive applications it might offer a general improvement over manual interaction.

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