Equinox: Exploring Naturalistic Distortions of Time Perception

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ABSTRACT

Subjective estimates of duration co-vary with emotion, focus, and task engagement in laboratory tests. Outside of the lab, the structural role of ubiquitous time-keeping devices has largely prevented the naturalistic study of this phenomena. In this paper, we present a new watch interface– called Equinox– designed to study time distortion in ecologically valid settings for the first time. Among other interactions, Equinox invites a user to guess the time in order to reveal the time. We test this novel interface with a small set of initial users to evaluate the practicality of naturalistic time perception research. Our work provides opportunities for future interfaces that might capture time distortion measurements as an objective marker that co-varies with the daily dynamics of user arousal, engagement, and emotion.

CCS CONCEPTS

• **Human-centered computing → Ubiquitous and mobile computing design and evaluation methods**; **User centered design**; • **Hardware → Sensor devices and platforms**.

ACM Reference Format:
David B. Ramsay and Joseph A. Paradiso. 2022. Equinox: Exploring Naturalistic Distortions of Time Perception. In *1st ACM Workshop on Smart Wearable Systems and Applications (SmartWear'22), October 17, 2022, Sydney, NSW, Australia.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3556560.3560713

1 INTRODUCTION

Our perception of time varies with our experience. Time flies when we are deeply engaged in 'flow' (i.e while playing music or sport) and slows when we are highly aroused or stressed (i.e. during a car accident) [9, 27].

These distortions of perception have been studied in controlled laboratory situations (like during a video game or while looking at emotionally evocative images) and in specific, extreme situations (like cave exploration or free-fall), but have not been studied in daily routine. Clocks are ubiquitous, which makes the phenomena difficult to capture; at the same time, laboratory results suggest time distortion can provide us with unique, quantitative insight into phenomenology of attentional states.

This relationship is important. The quality of our attention while engaged in a task is a better predictor of happiness than the task itself [17]; moreover, according to psychologists who studied well-being like Maslow and Csikszentmihalyi, mental states that correlate with time distortion represent an integral, experiential constituent of a well-lived life. Similar views permeate movements for 'calm technology' or 'slow computing'. As a result, time perception has become an area of increasing focus within HCI [18, 21], and shaping time perception is an explicit interaction design goal [34].

This research explores the possibility of extending time perception research to naturalistic settings. We present a new wearable called 'Equinox' specifically created to enable daily time perception research, and tested it with a small set of users to understand the feasibility of ecologically valid time perception measurement. The contributions are as follows:

- We present a new watch interface specifically designed for time perception study. To our knowledge, this is the first intervention targeting the study of time perception across normal daily experiences.
- We present a novel time perception time experimental paradigm. In order to integrate into modern life, Equinox asks participants to guess the time when they need to check the time (we refer to this guess of the clock state as a 'clock-time estimate'). To our knowledge, clock-time estimates are a novel approach to study perceptual distortions in the time perception literature; time perception literature exclusively uses intervals or durations.
- Equinox was evaluated by seven initial users over 31.8 hours in their normal lives (playing sports, working,

SmartWear'22, October 17, 2022, Sydney, NSW, Australia

ACM ISBN 978-1-4503-9524-3/22/10.
https://doi.org/10.1145/3556560.3560713

Figure 1: The custom 'Equinox' watch can notify the user, monitor ambient light levels, and collect time estimates, duration estimates, or experience sampling survey data all day long. In our initial test, we ask users to guess the time in order to check the time.

etc). This data provides insight into the feasibility of naturalistic time perception study. We aim to answer a few questions: (1) Can we collect meaningful time perception data at all during a user's normal, highly scheduled life, and on what time scales? (2) Do people experience meaningful and varied time distortions on a daily basis? (3) Are there obvious trends in the data that suggest clock-time estimates are a feasible or valid way to approach time perception research?

- Finally, we summarize our lessons learned to inform future design work.

2 BACKGROUND

William James famously suggested that 'varied and interesting experiences' feel short in the moment and long in retrospect [16], and the data has borne him out. Prospective time-keeping (where the user is informed ahead of time that they will be asked to estimate duration) are usually more accurate and less compressed than retrospective assessments. [3, 15] There is less research on longer time estimates (hours to days), but the studies that have tested these intervals suggest similar trends [2, 32].

Time perception is usually measured prospectively by estimating, producing, reproducing, or comparing durations [10, 30]. While production has been used to assess perception of intervals on the order of minutes (i.e., play this game until you feel 10 minutes have passed); for longer durations, estimation is the most common and practical strategy.

2.1 Influences on Time Perception: Arousal, Attention, and Environment

Emotional state alters time perception [8, 31], but recent work suggests the mechanism is mediated by arousal, a.k.a. the intensity of a felt emotion– for instance, sad faces do not have the same effect as frightened ones. [7] Research in depressed patients corroborates a relationship between time perception and arousal [30]. Increased arousal during short, adventurous activities slows time up to 30%. [27]

Deep focus is another cognitive state that alter time perception dramatically. Time estimates are 40% underestimated during hypnosis [26], during video games [20, 25], and in 'flow states' [13]. It is common to see this relationship exploited to interrogate video game immersion [20, 24].

Environmental cues also can alter our perception of time. Time spent building small scale models of i.e. trains or ships appears to compress time [19]. Moreover, light-deprived cavers will drift towards a 48 hour circadian cycle and underestimate their time underground by about half [12].

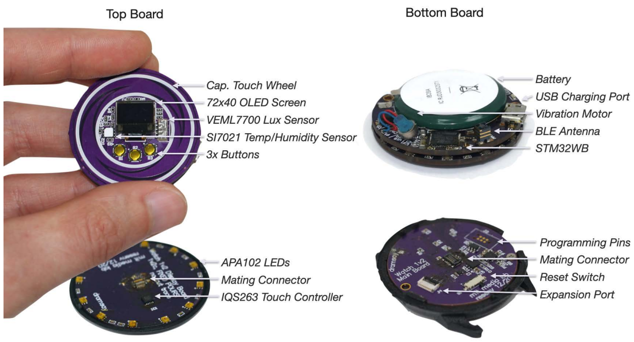

Figure 2: The two PCB design of the Equinox watch. This design sandwiches two boards together, so that the top board can support a large, flat touch interface. Individually addressable LEDs emit light around the mid-plane of the watch.

2.2 Models of Time Perception

While there are challenges unifying a theory of time perception with the variability introduced by memory, duration, and task structure, the 'pacemaker-accumulator' model first proposed by Treisman in 1963 is still dominant [33]. This two-part model is comprised of an internal clock (influenced by arousal/environment) generating ticks that are counted by an accumulator (influenced by attention) and filtered through memory. Some intrinsic neuro-scientific models [8, 29] support this conception, though other modality-specific models are gaining traction (i.e. 'dedicated' neural circuits just for motor prediction and timing) [1, 29].

3 EQUINOX

A watch interface is a minimally disruptive, well-received interface for psychological experiment [14] and is one of the only ways to preempt phone-based time checks. Equinox (Fig. 1 & 2) is a custom watch interface that captures white light/overall light levels, temperature, and humidity; it syncs with a phone over BLE and keeps track of the time accurately. It provides a 72x40 OLED display, three tactile buttons, twelve LEDs, a vibration motor, and a capacitive touch wheel for user interaction. The watch communicates to a cross-platform native smartphone application, and authorizes and uploads data to a Firebase database instance which synchronously supports multiple watches and users; it is also programmed with a range of interactions including duration estimates, clock-time estimates, and experience sampling. Equinox is an open hardware design, with PCBs available at https://oshpark.com/profiles/dramsay. A bill of materials, custom firmware code, mechanical design files, and the companion application code are all available at https://github.com/mitmedialab/equinox.

3.1 Design Considerations

Sensor selection and UI design considerations in Equinox are driven by the need to adapt laboratory time perception measurement instruments to daily life, embody them such that they're usable and reliable, and to collect secondary environmental data that might influence timing judgement.

We prioritized measuring time perception over minutes to hours, to ascertain a picture of time distortion across a full day, with interaction support for both duration measurements (*where the user starts the watch, and then estimates the elapsed number of minutes when prompted*) as well as clock-time estimates (*guess the time when you need to check the time*). The device provides enough UI degrees of freedom to prototype any major time perception task.

We included secondary measures of temperature and humidity because they can indicate indoor/outdoor context switches [5], influence arousal level [11], and provide an ambient baseline for additional skin-temperature arousal monitoring techniques [6]. We also include ambient light measurements, as peripheral light can be a powerful indicator of time passing [12, 28]. These measures give us insight into arousal and environmental cues– the two main factors outside of engagement– that might affect time perception, especially when paired with additional wearables [4, 23].

We want to integrate time perception measurement into a user's life in a way that is minimally disruptive and practical. Users need to check the time frequently; moreover, almost every screen-based UI immediately greets users with the current time, making it difficult to hide explicit time cues from users. We designed our interaction as a minimally invasive, easy to bypass interaction that provides the current time immediately, with minimal overhead, and which can be easily dismissed and reset should the user receive an external cue.

Our desire for minimal disruption during field use also informed our engineering goals– all day battery life, responsive and precise touch UI, data caching when operating without a nearby phone, accurate time-keeping, and easy charging.

Finally, we had a desire for researcher usability, enabling flexibly prototyping of various time interactions, seamlessly data collection, and easily integration with a wider wearable ecosystem. Hardware and software transparency is integral to physiological monitoring [22]; this platform affords hardware upgrades and extensions, alongside easy cross-platform app development with a single toolchain. This makes Equinox useful, open-source prototyping platform for others.

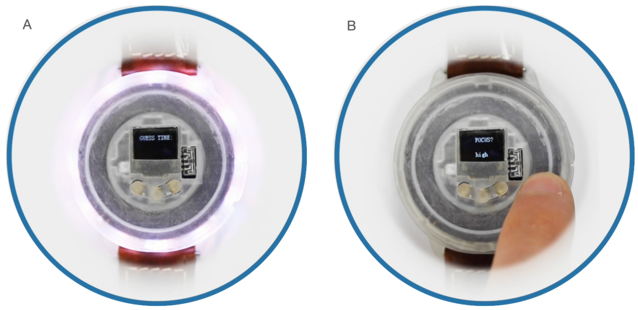

Figure 3: Two possible interactions with Equinox. (A) shows the watch vibrating and lighting up to prompt a user to guess the time, (B) shows an example of an ESM survey where the bottom of the touch dial maps to a 5-point likert scale rating. For our main exploratory analysis, we allowed the user to initiate a 'guess time' interaction, and displayed the current time immediately after their guess.

4 EVALUATION

4.1 Preliminary Stages

We started with a preliminary engineering evaluation to check that all engineering systems were successfully capturing a range of realistic conditions (i.e. direct light, cold temperatures), and that data was correctly cached when out-of-range of a BLE master device, and that the touch controller provided smooth, single-minute resolution data entry. Battery life was >10hrs in all tests, and clock drift never approached 1 minute (our lowest resolution).

We performed short interviews with potential users, to inform a few preliminary design decisions before running our initial usability study:

- **Time Intervals.** After building the watch to support up to 15 second steps, we decided on 1 minute resolution, based on how frequently we expect people to check the time.
- **Clock-time instead of Duration.** Duration measures require the user to initialize a timer, and should be rendered invalid if they see a clock (a peripheral time cue) during that test. We decided against this interaction because (1) it puts an initialization burden on the user, which they must remember and which primes them prospectively (retrospective measurements are preferable because they show more time dilation), and (2) it creates a parallel, secondary timing task from the primary user timing task of tracking their daily schedule. This adds a lot of friction, and room for unwitting bias from checking the clock in parallel. We instead decided to integrate the time-perception measurement into the time-monitoring process people already engage with. We use the natural instinct to check the time to capture measurements; it also makes 'mistakes' more clear to users (glancing at a clock during a task where you estimate the clock-time obviously invalidates that interval; this is less obvious for duration estimates).
- **Expectations of 'Mistakes'.** Participants were willing to put post-it notes over clocks around their workspace and switch to push calendar notifications to alert them for meetings. We still expect many intervals throughout the day to be invalid because of scheduled cues or clocks; thus, we designed an interaction to accommodate these frequent 'failures' with the tap of a button.
- **Natural Breaks instead of Interruptions.** Instead of interrupting the user to initiate a clock-time estimate after a random interval with a vibration and light alert (Figure 3), we decided to allow the user to use the watch as they normally would to check the time, but with a short preceding interaction (either guess the time, or hit a button to indicate you'd seen a clock or received a reminder since you last looked at your watch). This interaction is easy to bypass if the user is in a rush; it also maximizes the interval lengths we can study naturalistically, and gives us an additional signal into user stress and focus (i.e. we expect stressed/distracted users will check the time more frequently).

Our final interaction was designed with speed in mind, knowing how frequently people must check the time. When the user touches the dial of the watch, it enters 'guess time mode'; releasing the dial locks in that guess and quickly reveals the actual time. This interaction requires a single gesture, without buttons. Users who have noticed the time elsewhere can instead hit a button that will bypass the 'guess time' interaction, show the time, and reset the interaction.

4.2 Primary Exploratory Study

Using this interaction, we collected 32 hours worth of data with 7 initial users in our building (age 25-34) in their normal, naturally-lit workspace, with no constraints on work tasks. Fig 4 shows the resulting 59 time estimates taken between 7 min and 1 hr 51 min after last checking the time (mean=33.5 min). No users reported major input errors, though some reported surprise at their accuracy (both good and bad).

Our data shows that average time estimate error was 12.5 minutes (after accounting for off-by-one-hour mistakes). Errors heavily favors time compression at an average 7.4 minutes short (22.1% of the actual duration). These time errors reasonably match expectation of retrospective, duration-based time perception lab research. [26, 27] For durations over an hour, estimates tend to favor 5 minute increments.

Over twenty of our estimates were after 5PM; a comparison between daytime and evening time estimates showed

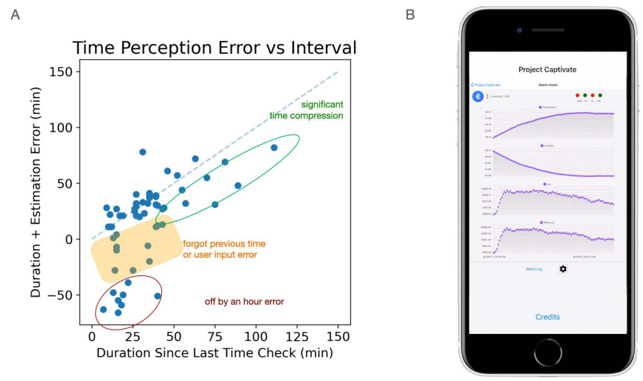

Figure 4: Resulting Data from Equinox study. (A) compares the duration since the last time a user checked their watch (x-axis) with the duration their estimate (so if they checked their watch at noon, and then guessed it was 12:15 at 12:20, we'd see a point at (20min, 15min)); (B) shows continuous light level (white and full-spectrum), temperature, and humidity data displayed in the custom iPhone application, which synchronizes data with a secure online database.

no meaningful differences, though this data is preliminary (evening errors = 10.8 min ± 10.9, day errors = 13.4 min ± 11.0, average time since last check = 31.0 vs 34.9).

5 DISCUSSION AND FUTURE WORK

In this paper, we present a novel, open source interface for naturalistic time perception measurement, and validate some basic assumptions by using it in a 32 hour pilot study. We were able to collect high quality data over the course of the study which validates that (1) naturalistic time perception measurement during a normal workday on the order of 10-45 minutes is possible and (2) users experience significant and measurable time distortion in normal life that we can capture, especially as intervals grow.

This preliminary data shows no obvious major differences between clock-time estimates during unscheduled, dark evening hours compared with the workday, which suggests the influence of peripheral cues may not be as significant a factor as we had initially anticipated.

The raw data reveals some fascinating trends. We would expect long duration, 'in-the-zone' work periods to have some of the most significant time compression, which they do. However, clock-time estimates have unique errors compared with typical duration techniques. Three users made off-by-an-hour errors, which suggests they were conceptualizing the task as a prospective duration task ('how many minutes have passed?') and focused only on the minute value.

Another three users made estimates that were not off-by-an-hour, but still greater than the interval since the last time they checked the watch (i.e., checking the time at 11p, then guessing at 11:30p that it's 10:57p or 11:02p). Given the frequency of this phenomena, we hypothesize that users don't memorize the time precisely (i.e. 1:43PM), and instead conceptualize its meaning (it's a early afternoon and I still have a while before my meeting) in a way that can be very forgettable if they have no incumbent commitments.

These errors raise some interesting questions about how to properly handle the data we receive; clock-time estimation may not directly map to a rigid prospective/retrospective paradigm. With continued use and habituation we might expect 'more retrospective' assessments, though the overall trend between focus and time distortion in both cases is similar. These data begs interesting questions about how we conceive of time in our daily lives– how should we interpret a failure to internalize the time when glancing at the clock?

Our work suggests ecological data is varied, insightful, and worth capturing. It also raises questions important to future naturalistic study specifically and time perception research generally. Future studies will collect more data; pair the watch with other wearables; extend the work to include experience sampling of related cognitive phenomena; and more rigorously evaluate environmental covariates.

Most importantly, we plan to further explore clock-time estimation as a technique, and compare it more robustly to duration specific estimates. Future work will focus on further understanding the mental processes behind clock-time estimation and how they differ from and interact with standard time perception research practice. This question is central to naturalistic time perception work, as clock-time is central to naturalistic living and will always confound time perception research in the wild.

Moreover, the common errors we find in wall-clock estimates suggest variability and complexity in individual approaches to clock-time estimation, and suggest that we frequently fail to internalize (hold in working memory or shift to long-term) exact numerical clock-time representations. Beyond time distortions, our data suggests the frequently with which a user checks the time and forgets the time may also provide quantitative insight into user phenomenology.

6 CONCLUSIONS

In this paper, we present an open-source platform for the naturalistic study of time perception. Equinox has successfully demonstrated the feasibility of this agenda. With it, we measured high levels of time distortion in our participants' daily lives, alongside a new method for time perception measurement– the clock-time estimate.

We plan to use the lessons learned from this exploratory study to refine and expand our data collection techniques. Naturalistic studies provide an opportunity to vastly scale data collection compared to lab-constrained designs, which will be crucial to improve our underlying models of time perception. Ultimately, tools like Equinox will allow us to infer engagement and emotion from time distortion in a quantitative way so that we can evaluate the design and impact of our tools and our environments to increase the depth of our engagement– and thus our happiness– with our daily experiences.

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