Context-aware Adaptive Visualizations for Critical Decision Making

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ABSTRACT

User interface adaptations for Information Visualisation have yet to unlock their potential in critical decision-making scenarios, like emergency rooms or self-driving cars. We argue that future solutions should consider a user-centric approach guided by context awareness and emotion sensing capabilities. In this regard, we propose an innovative adaptive framework inspired by symbiosis principles where humans and machines cooperate and co-evolve to support decision making processes. We also discuss the most pressing challenges in adaptive user interfaces to achieve this vision and propose a series of integrative solutions to advance the field.

CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**; *HCI theory, concepts and models.*

KEYWORDS

Adaptation; Interface Personalisation; Design; Environment

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1 INTRODUCTION AND BACKGROUND

Information overload is the by-product of information over-exposure which, nowadays, has become an aggravated phenomenon. Simply put, when presented with a large array of options, users are at a higher risk of experiencing impeded cognitive functioning, which may reduce their capacity to perform effective decision making, derive meanings, and gain insights, especially in situation- and time-sensitive contexts. While using visualizations to mitigate this effect has been widely discussed as a possible countermeasure [12], the potential of adaptive Information Visualisation (InfoVis) systems has not yet been unlocked to best assist the user in critical decision-making tasks.

InfoVis technologies provide a way to expand and enhance our innate cognitive abilities, and enable us to accomplish a range of tasks, from simple (e.g. company revenue assessment) to intractable (e.g. air-traffic control). However, depending on the timing and context, we may have a greater or lesser ability to make rapid and effective decisions. Yet our ability to do so based on fast-flowing streams of data may be decisive. In this regard, we argue that Artificial Intelligence (AI) enhanced with context-aware attributes will play a key role in leading the necessary advancements for next-generation adaptive InfoVis systems.

To fulfill this goal, we need to define what is "awareness" and how to implement it computationally. Researchers have proposed several definitions, including philosophical [7, 21], psychological [15], architectural [1, 9], neural correlates [8], and computer science theory [6]. Yet researchers have shed little light on the issue of the origins of our subjective experiences, also known as the "hard problems" [7]. Much progress has been made with what is described as "easy problems", which relate to access-to-information issues, like understanding our ability to categorise environmental stimuli and the deliberate control of behaviour [7]. Solving the hard problems depends on developing a greater understanding of human working memory. In this regard, according to Humphrey [14], awareness has a strong social dimension that cannot be ignored. Humans have existed in social groups for tens of thousands of years, and thus had to predict, understand, and manipulate the behaviour of others. Also, according to Baars [5], awareness is the main component of our cognitive processing system, responsible for functions such as adaptation and learning, decision making, self-monitoring, and self-maintenance.

Inspired by this prior body of research, we pose that *awareness is a latent property of a properly organized system.* As explained later, we further incorporate basic elements of social functioning (or even priming) by means of an altruistic, multi-agent environment, as well as emotion recognition capabilities (via cross-modal communication) for establishing the sensing and the affective, which play a fundamental role in our social interactions.

This framework facilitates a more natural dialogue between humans and adaptive systems to support critical decision-making processes. Importantly, this requires that machines are equipped with

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emotion sensing and expressing capabilities. Dehaene [9] argued that most AIs fall within a C0 stage of "unconscious processing", although we can find examples of so-called super-human behavior in computer vision [11], machine translation [4], and game playing [16], among other tasks. However, truly intelligent systems must be equipped with a new form of awareness. Following Dehaene's principles, a C1 stage of global availability is needed, possibly together with a C2 stage of self-monitoring or meta-cognition. With these abilities, machines can start to reason, which increases their potential as intelligent partners. To this end, we have chosen to deviate from classic exploration mechanisms for decision making and propose the investigation of exploration-conscious criteria that will allow for adaptation and learning to be manifested in a more autonomous manner.

2 FROM SCIENCE TO INNOVATION

There are many ways to visually represent data in order to support decision-making tasks, mostly guided by domain expertise. We propose a novel approach: AI-guided visual adaptation supported by conscious-like decision making agents that can act synergistically and are equipped with context-aware capabilities. While state-of-the-art computational models have been successful in predicting expert performance in a range of tasks, much work remains to be done in modelling how other types of users (e.g. novices) gradually become more skilled and how the visualisations may adapt intelligently to suit their needs.

Previous work investigated how information should be presented in order to reduce cognitive load and enhance the efficiency and effectiveness of decision making. Among those, we should mention the cognitive fit theory [23], which states that, when there is a correspondence between the task and the information presentation format, it will lead to superior task performance for individual users. The theory has been applied to the InfoVis domain, where it has been used to explain performance differences among users on adjacency, proximity, and containment tasks [10, 17]. However, this theory has also been shown to be inconsistent when it comes to explaining information overload [12] and arguably leaves ample room for modern data-driven approaches guided by recent advancements in AI research.

We instantiate three cognitive hypotheses about learning, memory, and vision to model user interactions with InfoVis systems. The main converging principles are associative learning [1], utility learning [2], and feature guidance [24]. To this end, we envision a bidirectional channel of communication between AI and human users, which taps directly to human cognitive resources for facilitating an effortless and natural dialogue. The said dialogue will be based on a common vocabulary (a mechanistic understanding) of important regulatory and utilitarian functions within the human body and brain that facilitate rational decision making and perception. The building blocks for this dialogue can be cardiovascular, respiratory, electrodermal, metabolic, and other neurophysiological responses (captured via unobtrusive, wearable sensors), all of which are considered objective and accurate measurements of cognitive phenomena of interest that cannot be captured by any other means, or at the desirable throughput. Figure 1 provides an overview of the our envisioned system architecture.

Our research vision is currently being developed in the EU-funded project SYMBIOTIK.[1] The project provides AI agents with awareness of the environment via the provision of an embedding space of cross-modal, neurophysiological descriptors captured with commodity sensors. This interdisciplinary technological innovation is, in itself, an enabler of the further integration of AI and human users in future InfoVis systems, which, up to this day, has only seen limited or incremental advancements.

3 CURRENT CHALLENGES

In the following we describe what we believe are the most pressing issues and limitations in today's adaptive user interfaces and propose a series of integrative solutions to advance the field.

3.1 Rule-based adaptation has reached its limit

With sophisticated adaptive systems, the number of adaptation rules significantly increases and becomes unmanageable. Take for example the VIRTUOSO system for managing steel production in Belgium and India.[2] It comprises an adaptive InfoVis panel based on 130+ adaptation rules, and is still growing: the more rules are added, the more exceptions are introduced. It is then clear that hand-crafted rules are not scalable, may clash with others, and become challenging to manage manually. Progress beyond the state of the art should consider Machine Learning (ML) approaches to automatically infer the right adaptation rules. In this scenario, the role of Reinforcement Learning (RL) may be instrumental in addressing this technological impasse, as demonstrated in recent work on adaptive menus [19]. However, making this possible will require new innovations that bring to bear sophisticated statistical methods and combine them with the fundamentals of sequential decision making that are conventionally studied in RL.

ML-driven methods have the potential to mitigate the shortcomings of earlier approaches, by explicitly accounting for the aforementioned distributional shift (i.e. given data that resulted from a given set of decisions, infer the consequence of a different set of decisions) that rule-based systems cannot address at scale, either by constraining the policy's deviation from the data, estimating epistemic uncertainty as a measure of distributional shift, and facilitating generalization.

3.2 Only machine learning is insufficient

While modern ML induces a solid statistical data-based approach, it is often hard to explain and interpret, whereas model-based (i.e. analytical) approaches give more rationale and predictability to the user. Therefore, progress beyond the state of the art should consider a combination of both approaches, to marry the best of both worlds.

The use of transparent decision making algorithms will be conducive in addressing this technological challenge. By expanding on a recent multi-objective deep RL framework [18], it is possible to create RL algorithms that afford explainability and introduce desirable properties in an unequivocal manner. Moreover, given the competitive nature of many real-world problems, objectives

[1] https://symbiotik-infovis.eu/

[2] See https://www.polemecatech.be/en/projets/virtuoso/ and https://youtu.be/3mI5_DeKOrY.

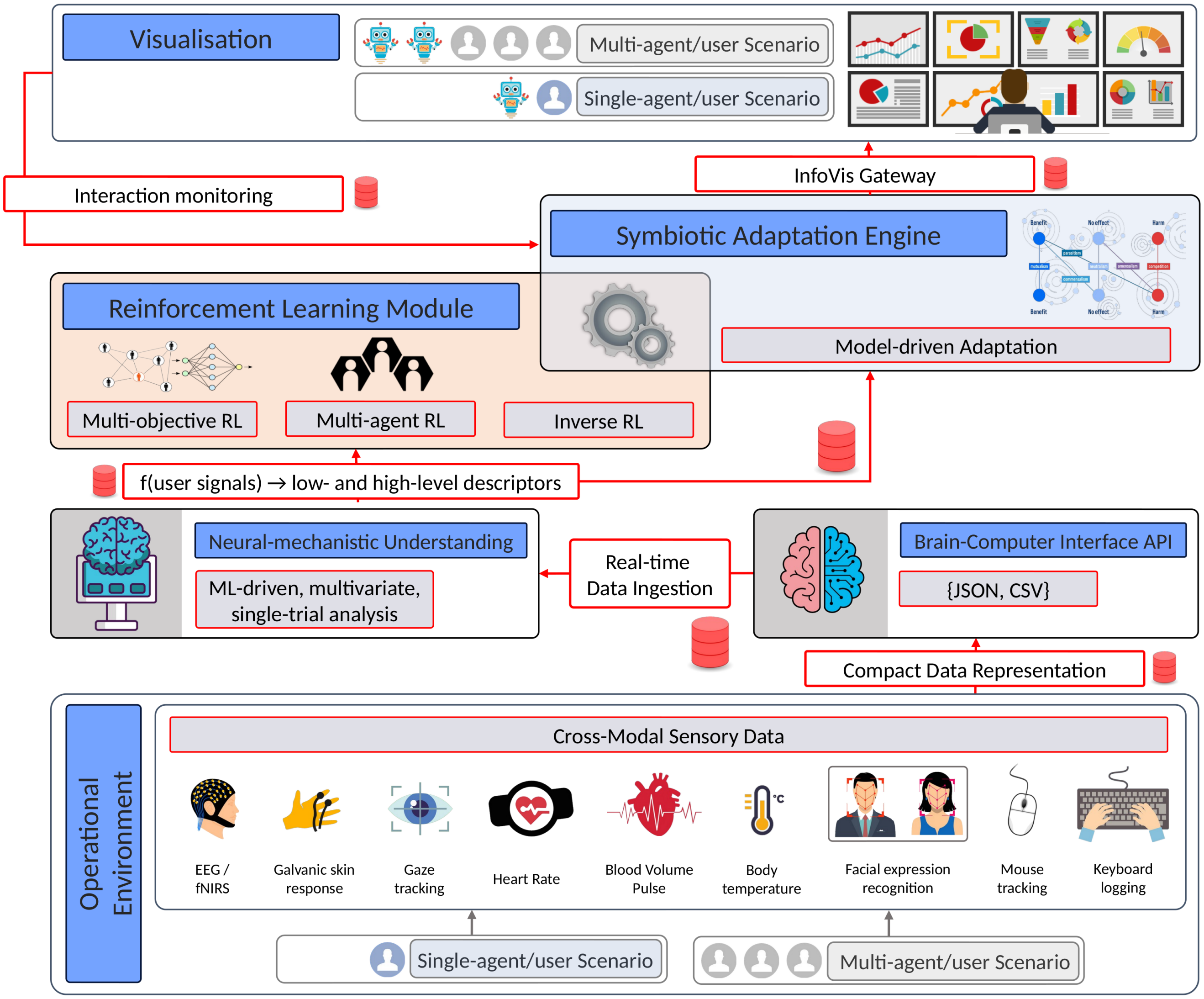

Figure 1: Architecture diagram of the SYMBIOTIK project.

are often affected by other users. As such, we should consider a multi-objective multi-agent approach, where altruistic agents see the interests of other agents as objectives and aim to come up with fair solutions [3].

3.3 Enhancing adaptation through context-aware agents

Until now, adaptive systems have mostly investigated the extreme positions of adaptation (e.g. some adaptability with the intervention of end-users or adaptivity with only system intervention) but not much of a truly mixed-initiative approach, where end-users are included "in the loop". Progress beyond the state of the art should consider varying degrees of involvement according to the use context; see e.g. the Adaptation Automation Levels proposed by Todi and co-authors [20].

We believe that end-users need to be an integral part of adaptive systems, where both AI and human cognition can have complementary roles. This symbiotic relationship will help alleviate the issues of extreme complexity and variability observed in human cognition. For example, two users looking at the same dashboard will derive very different insights from it, depending on their backgrounds and profiles. To this end, we need to determine the use conditions that result not only in a secure environment [22], but also in enhanced performance, smarter decisions, and quicker response times in critical situations, by introducing neuro-feedback in the interaction loop and through the integration of context-aware AI agents.

3.4 Limited input for adaptation

The more information about the user is available, the more precise the adaptation becomes; at the cost of increasing concerns about privacy or invasiveness of the measuring devices. Progress beyond the state of the art should consider a tradeoff between these measures and the adaptation quality. For example, if the optimal solution does not fit the current regulations,[3] then a suboptimal solution must be adopted.

In this context, future adaptive InfoVis systems should include algorithmically transparent approaches that can maximize human perceptual abilities and lift cognitive competencies to new levels. At the root of this initiative lies our current knowledge on the strengths and weaknesses of certain human functions, e.g., that visual functions are extremely fast and efficient processes, whereas cognitive processes —the act of thinking— are much slower and less efficient. Thus we need to minimize the amount of thinking or "working out" that goes into reading and interpreting data, and simply let the eyes do their efficient and effective job.

3.5 Lack of adaptation-centered measures

In terms of decision making, certain information may be ignored if it does not match expectations, if other information is more salient, or if it is presented in a more attractive way. Several measures are able to quantify some aspects of a display, such as visual clutter, object salience, aesthetic metrics (e.g. symmetry, balance, density), colourfulness, etc. but they are not specifically tailored to user interface adaptations.

Progress beyond the state of the art should envisage novel user-centered measures. For example, eye tracking methods can detect information that is not perceived (therefore, estimated as ignored for the current task), perceived but untouched (therefore, estimated of little usefulness), and perceived followed by an action decided (therefore, useful for the task at hand). To enable more semantic and adaptation-centered measures for InfoVis systems, we should consider approaches such as the Perception-Decision-Action life cycle [13]. This way, computers can deliver plausible interface adaptations that balance the tradeoffs of positive and negative changes performed to the interface.

4 CONCLUSION

Adaptive InfoVis systems can enhance end-users' cognitive processing in time-critical contexts as well as bringing awareness and emotional intelligence to computers. We have proposed a novel context-aware and human-centric framework that follows symbiosis principles. We also have argued that it is necessary to consider social and collaborative aspects of user-AI interaction with InfoVis systems, orchestrating highly complex and collaborative ways of working, while augmenting our visual functions to empower our cognitive functions. Taken together, these innovations will lead to better approaches for shaping the future of adaptive interfaces.

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[3] See https://gdpr.eu/ and https://artificialintelligenceact.eu/