2 A FRAMEWORK TOWARD "LIMINAL INTERACTIONS"

> *"The best computer is a quiet, invisible servant."*
> *"The purpose of a computer is to help you do something else."*
> *"Technology should create calm."*
> *"The more you can do by intuition the smarter you are:*
> ***the computer should extend your unconscious**."*

— Mark D. Weiser, 1996[1]

In a typical Human-Computer Interaction (HCI), a person, usually awake and conscious, processes information and makes decisions and *inputs* to the computer. Usually, these inputs are through motor responses (e.g., using a mouse or a keyboard), which will control the computer and, finally, display the information as an *output* (e.g., a popup window). This traditional HCI model often considers the user as a conscious, thinking mind that is awake and aware of the *inputs* and *outputs* (from and to the machine). However, in our daily life, we are always in transition between different mental states, consciousness and attention arise and fade, we awaken and sleep, and user interfaces (UI) can also be more or less *implicit*. Hence, this thesis proposes a framework to categorize human-computer interactions based on the state of consciousness of the user and explicitness of the UI. I envision that these interactions can be transitory, or *liminal* (from the Latin word līmen, meaning "a threshold"). *Liminal* interactions can happen in-between mental states, evolve, and adapt how *implicit*/*explicit* their input/output (I/O) is. This framework's primary goal is to create a new form of interaction design that goes beyond *explicit*, conscious wakefulness interactions towards a wide range of states of consciousness that can smoothly transition and might benefit from *implicit* I/O.

2.0.1 Human consciousness and computer interaction

Human-computer interaction has traditionally focused on designing technologies and studying how humans consciously interact with them. However, in our daily lives, a considerable part of our behavior and decisions are the result of unconscious processes rather than rational decision-making. Our thoughts and behavior are heavily influenced by our sensory perception of the environment and previous experiences. Despite this, the field of HCI has almost exclusively focused on designing interfaces and applications that view the user as a conscious, rational thinking mind. Most technologies require a high level of conscious awareness and focused attention to interact with the system. However, there has been an increasing interest in creating user interfaces that are less *explicit*, more subtle, and less demanding to the user. An important aspect of these systems is that they do not require the user to pay close attention to the device or the interaction. They are designed to stay in the user's periphery and to smoothly shift to the foreground of the user's attention when required. Some pioneers that paved the way to this type of research date back to the '90s, such as Ubiquitous Computing by Weiser [1993], Calm Technologies (Weiser and Brown [1996]), Ambient Media displays (Ishii et al. [1998]) as well as

1 Weiser, Mark (November 1, 1996). "Computer Science Challenges for the Next 10 Years". Minute 43:31: https://youtu.be/7jwLWosmmjE, '90s

more recent work such as Implicit HCI by Schmidt [2000], Slow Technologies by Hallnäs and Redström [2001] or Ambient Interfaces by Gross [2003].

By standing on the shoulders of these giants, this thesis explores how some of these visions, theories, and frameworks can evolve and be enriched by research in cognitive science and psychology to inspire new types of human-computer interactions and design of novel user interfaces.

2.0.2 Dual process theory in psychology

The psychological origins of the distinction between rational and irrational thinking, *explicit* versus *implicit* or conscious versus unconscious can be traced back to 1890 when William James proposed that there were two types of reasoning, *Associative Reasoning* and *True Reasoning*, which were the foundations of the *Dual-Process Theory*. Contrary to popular belief, Freud did not invent the term *unconscious* or *subconscious*, Friedrich Schelling in 1800 coined the term, which was later examined and further researched by William James in his book (see Weinberger [2000]).

In 1900, Freud named these processes: *Primary Process* and *Secondary Process*, which evolved to many other names (as seen in Figure 2.1), such as *Intuitive Reasoning* and *Extensional Reasoning* by Nobel Laureate Daniel Kahneman and Amos Tversky. Kahneman [2011] described two different ways the brain forms thoughts as seen in Figure 2.2: ***System-1***: Fast, automatic, frequent, emotional, stereotypic, unconscious. ***System-2***: Slow, effortful, infrequent, logical, calculating, conscious.

Author	Model/Theory	Year	**Implicit (automatic), unconscious process**	**Explicit (controlled), conscious process**
William James	Dual-Process Theory	1890	Associative Reasoning	True Reasoning
Sigmund Freud	Dual-Process Theory	1900	Primary Process	Secondary Process
Tversky & Kahneman	Dual-Process Theory	1974	Intuitive Reasoning	Extensional Reasoning
Shelly Chaiken	Heuristic Systematic Model	1980	Heuristically	Systematically
Jonathan Evans	Dual Process Theory	1975	Heuristic Processes	Analytic Processes
Richard E. Petty and John Cacioppo	Elaboration Likelihood Model of Persuasion	1986	Second or Peripheral route of thought	First route of thought
Steven Sloman	Two-Systems Theory	1996	Associative System	Rule-based System
Stanovich & West	Two-Systems Theory	2000	System 1	System 2
Ron Sun	Dual Process Learning Model (CLARION)	2002	Implicit Learning	Explicit Learning
Daniel Kahneman	**Two-Systems Theory**	**2003**	**Intuition or System 1**	**Reasoning or System 2**
Fritz Strack and Roland Deutsch	Two-Systems Theory	2004	Impulsive System	Reflective System
Steven Sloman	Two-Systems Theory	2014	Intuition	Deliberation

Figure 2.1: The psychological origins of the dualist distinction between rational and irrational thinking can be traced back to William James (1890/1950) and Freud (1900/1953).

System-1	System-2
Automatic	Controlled
Fast Thinking	Slow Thinking
Intuitive	Deliberate
More influential than what your experience tells you	What we think about ourselves
Secret author of choices and judgments	Constructs a coherent interpretation of what is going in our world
Often Unconscious Processes	Conscious
Intuitive Thinking	Rational Thinking
Little or no effort	Effortful
Involuntary	Voluntary
Innate skills that we share with animals	Complex Computations
Born prepared to perceive the world around us, recognize objects, orient	Subjective experience of agency, choice & concentration

Figure 2.2: The table presents the two types of processes or types of reasoning defined by Daniel Kahneman and Amos Tversky. System-1 is often associated with unconscious processes, intuitive or automatic thinking. System-2 is deliberate, conscious, and rational thinking that requires more effort, concentration, and voluntary response.

Kahneman and Tversky applied this theory to behavioral economics, which leads into the question— **can the *Dual Process Theory* be applied as a psychological framework for decision modeling in Human-Computer Interaction?** With these interests in mind, the following sections provide the road map to a new HCI model inspired by this theory.

2.1 UI EXPLICITNESS

Implicit and *explicit* processes are the foundation of the dual-process theories in Psychology. These concepts have been sporadically used in HCI to describe the level of explicitness of the action (input) that the user performs to the computer. However, there is no clear consensus on how to categorize the output generated by the machine and the overall UI implicitness/explicitness (both inputs and outputs). There are currently no guidelines or common ground established to identify I/O on a taxonomic basis. Therefore, this framework defines the taxonomy of *Implicit/Explicit* HCI based on two axes: one for Input Awareness (how aware is the user of controlling the computer) and another for Output Awareness (how aware of the stimuli generated by the computer is the user). These interactions are not static in one specific state. They are a continuum from *explicit* to *implicit* and vice-versa, hence they might be *liminal* in between both of these extremes. Figure 2.3 showcases the overall UI explicitness representation, while Figure 2.4 and 2.5, the decomposed axes for the input and output, respectively.

1. Input Awareness: Figure 2.4 depicts a diagram to represent how aware are the users of producing input to the machine. For example, *explicit* is consciously moving the mouse, while *implicit* might be the heart rate signal of the user. An in-between, *liminal* state is when the user is not entirely sure that they are controlling the UI (e.g., during a user study, a participant is told that they can either be in a placebo condition or experimental condition and that the GUI might or might not change based on their biofeedback).

2. Output Awareness: Figure 2.5 shows the level of awareness that the users have of the output stimuli/feedback generated by the machine. For example, one can be highly aware of a popup window in the center of the user's attention (*explicit*) but might not be aware of a subtle smell in the environment, a subliminal message or feedback at the periphery (*implicit*). These outputs can also be in a *liminal* state, for example, if they move across space, from the periphery to the foreground of the users' attention, or if they start as supraliminal stimuli and they slowly turn into a subliminal one.

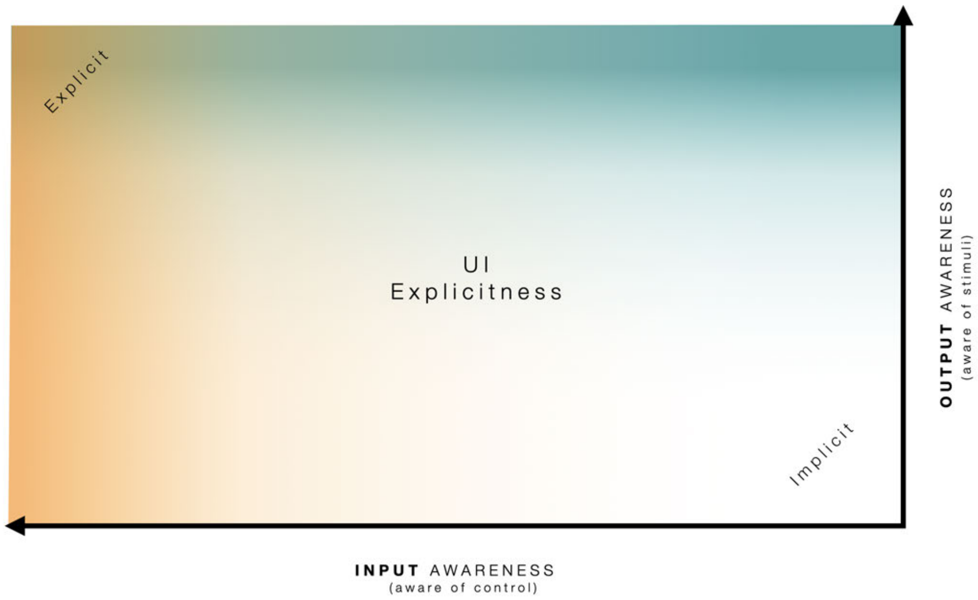

Figure 2.3: Representation of the User Interface (UI) Explicitness/Implicitness of the input and output based on how aware of the stimuli or of controlling the UI is the user. The opacity of the color increases with the level of awareness.

2.1.1 Input awareness

On the one hand, a user can explicitly control a UI, such as in the case of a traditional direct manipulation by Shneiderman [1982], Hutchins et al. [1985]), or by touching the UI like in Tangible Bits by Ishii and Ullmer [1997]. On the other hand, the user can input their physiological signals or context-based action to the system implicitly (a.k.a *implicit* input, see Figure 2.4).

Schmidt [2000], proposed the term *Implicit human-computer interaction*, where the form of the input to the system is a context/situation-based action and the output can change the volume, brightness, font size or privacy settings. In the paper, the author suggests that Implicit HCI can limit the need for input and interruptions by finding the most suitable time or context. His theory resembles "Ubiquitous Computing" by Weiser [1991] who said that *"(...) Today's computers, in contrast, have no idea of their location and surroundings. If a computer merely knows what room it is in, it can adapt its behavior in significant ways without requiring even a hint of artificial intelligence."*.

Other researchers like Robert Jacob define an *implicit* user interface as interfaces that *"passively obtain information from their users, typically in addition to the mouse, keyboard, or other explicit inputs. They fit into the emerging trends of physiological computing and affective computing"*[2]. In his work with Treacy Solovey et al. [2015], they presented a conceptual framework for considering *implicit* input from the brain, along with design principles driven from their research using near-infrared spectroscopy (fNIRS). In contrast to Schmidt, the *implicit* input in Jacob's work is based on the user's physiology, instead of the context. The output for these systems often adapts based on the input with an *explicit* visual change in the screen, or like Schmidt mentioned, with a brightness, font size, or volume change.

Beyond using brain activity or context-based inputs, I envision that other types of *implicit* inputs will emerge in the following years. For example, Picard [2000] explored Affective Computing using heart rate, heart rate variability, electrodermal activity, or facial expressions, or even tongue color (such as the work by Hernandez et al. [2017]). Other *implicit* inputs might use hormonal changes (Pataranutaporn

2 HCI Seminar series: https://www.csail.mit.edu/event/implicit-user-interfaces

et al. [2017]) or bio/chemical sensing based on ph or cortisol (e.g, by looking into biomarkers in saliva like the work by Pataranutaporn et al. [2019]). The user's natural eye movement can be used as an *implicit* input if it does not require to make specific eye movements to control the system (Jacob [1990]), as well as the pupil size (currently used to predict mental workload by Abdelrahman et al. [2017]). Unconscious speech patterns, such as speaking with longer pauses or monotone tone, can predict depression (Scherer et al. [2016]). Muscle tension, body posture, or other involuntary body responses such as bruxism (clench or grind of teeth during sleep or wakefulness) have also been associated with stress and anxiety by Ahlberg et al. [2013]. Respiratory changes can be used to categorize emotional states such as anger, fear-anxiety, joy-laughter, or sadness (Bloch et al. [1991]). Similarly, body movement and posture can convey emotions (Dael et al. [2012]). Many of these signals could potentially be tracked using an Electrogastrography (EGG) while also monitoring stomach activity (Vujic et al. [2019]).

Other unexplored areas for *implicit* inputs in HCI could use body odors or exhaled breath to predict health conditions. Volatile organic compounds emitted from the human body can reflect a person's metabolic condition and are related to various diseases (Shirasu and Touhara [2011]). One could even predict various form of cancer such as lung cancer (Peng et al. [2009]), prostate cancer (Asimakopoulos et al. [2014]) or bladder cancer (Sato et al. [2017]), amongst others. Body odors can also reflect the emotional state of a person, such as aggression (Mutic et al. [2016b]) or happiness (de Groot et al. [2015b]), and Smeets et al. [2020] recently discovered that different emotions produce unique chemical fingerprints. Therefore, in the next decade, I expect that we will be able to use smells and its chemical compounds as an *implicit* input to recognize emotions and diseases using advanced electric noses and machine learning.

Figure 2.4: Input Awareness: Representation of how aware is the user of their input to the UI. Darker orange color represents the explicitness of the input, while a decreased opacity (lighter orange or white) represents a subtle or imperceptible awareness of controlling the UI (for example, using physiological signals).

2.1.2 Output awareness

In comparison to the work aforementioned in which the output is an *explicit* change of volume, brightness, or font size, this framework also considers the possibility of an *implicit* output (invisible, seamless, or imperceptible to the user). This thesis uses the term *implicit* HCI when both the input and output are *implicit*. This vision might resemble the original message that Mark Weiser intended to deliver, which was that *"calm technology engages both the center and the periphery of our attention, and moves back and forth between the two. We use "periphery" to name what we are attuned to without attending to explicitly."*, Weiser and Brown [1996]. As well as by Ishii et al. [1998], who designed the "ambientROOM", an interface to *"provide information for background processing. It displays information through subtle cues of sound, light, or motion easily relegated to the periphery of awareness."*. Therefore, both in the case of Ishii and Weiser, the output to the system is *implicit* and does not involve deliberate conscious attention (as depicted in Figure 2.5). These systems can easily shift from the periphery (*implicit*) to the foreground (*explicit*); however, there is no reference on how the interaction might be depending on the users' state of consciousness (e.g., while sleeping), which this thesis and framework addresses.

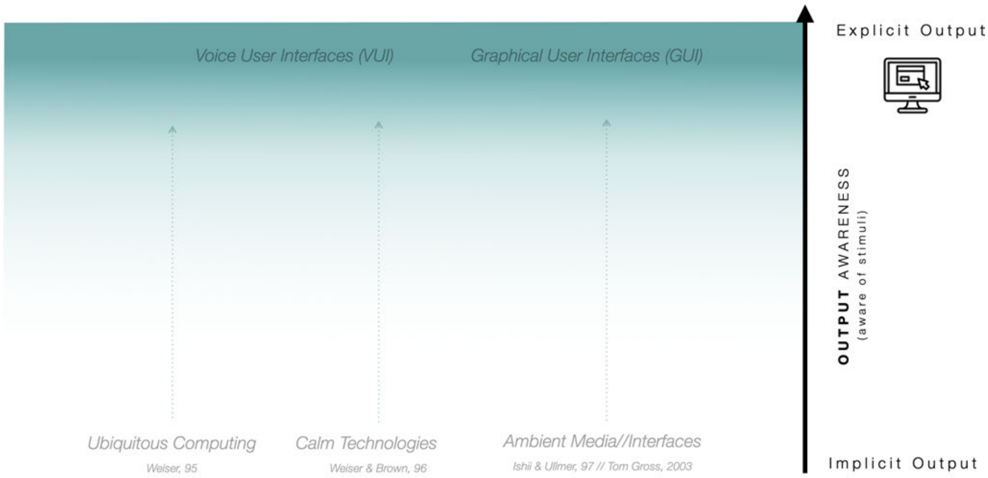

Figure 2.5: Users' awareness of the stimuli generated by the machine. The opacity of the color increases to a darker turquoise color when is more *explicit*; hence the user is more aware.

Olfactory interfaces are perhaps one of the best examples for these types of *liminal* interactions, as they move in the physical space and the periphery of our attention. For example, one might experience this by smelling the humidity of the air before the rain starts and after the downpour intensifies to a more intense earthy fragrance. This olfactory experience can fade very quickly from the foreground to the periphery of our attention (e.g., by focusing on another task or habituated to the smell). Similar experiences have been studied by researchers like Keller [2011], who report that olfactory consciousness is absent in the lack of attention. Therefore in this thesis, scent-delivery systems have been classified based on proxemics and their location in space (see Chapter 6 for more details). This dissertation also describes interaction design across different states of consciousness (e.g., *liminal* interactions that start during conscious wakefulness and continue while sleeping). In Weiser's or Ishii's view of foreground/background, they do not describe how these interactions might change depending on the user's consciousness state. For example, a computer can generate an *explicit* output (such a change of volume) that can also be used during deep sleep and therefore becoming *implicit*. One of the primary contributions of this framework is that it takes these types of *liminal* interactions into account by adding consciousness as a new dimension for HCI.

2.2 STATES OF CONSCIOUSNESS

What is consciousness? is perhaps one of the most challenging questions that science has been trying to answer. Research in Psychology, Philosophy, Neuroscience, and many other fields, has for decades, theorized and empirically conducted studies to understand what consciousness is and how it happens in the brain. Although there have been many advances, there are still plenty of challenges that remain unknown. As the science of consciousness matures, there is a growing need to guide the technological development of user interface designs based on these findings. The majority of HCI focuses on conscious rational thinking that does not take account if the user is in a non-ordinary state of consciousness. For example, during sleep, unconscious, in a comatose state, or under the influence of drugs. Therefore, this framework proposes an extension of the contemporary representation of consciousness for the context of Human-Computer Interaction.

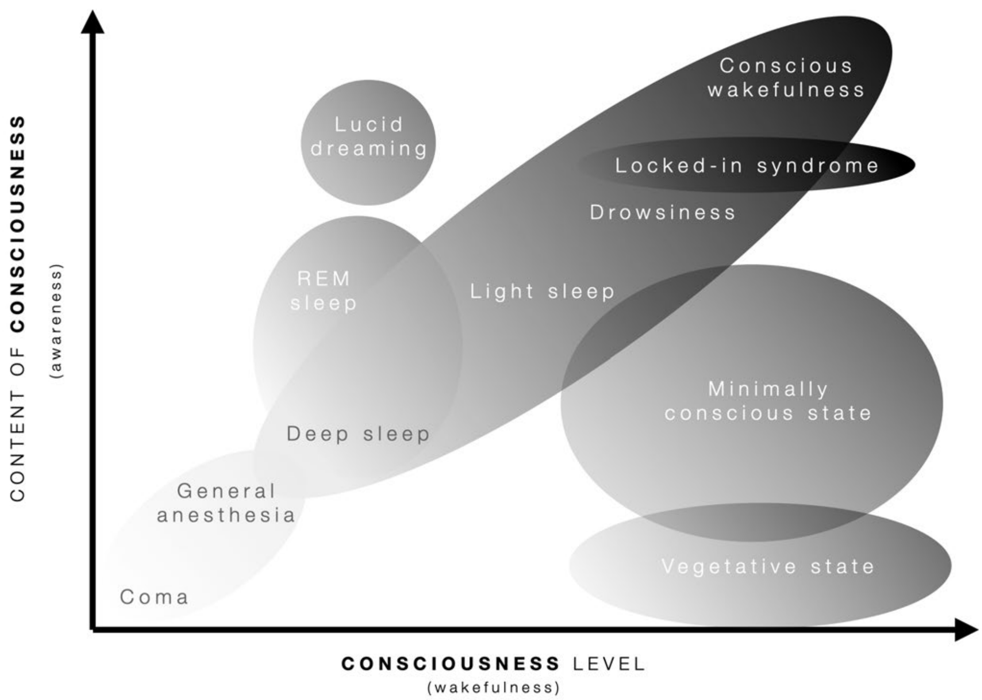

Figure 2.6: Diagram based on the traditional representation of consciousness, adapted from Laureys [2005] and Stokes et al. [2018]. One axis is the level of consciousness (wakefulness or arousal), and the other axis is the content of consciousness (awareness or experience). The depth of the consciousness level of the user is mapped to the darkness of the color. Where the darker is the color, the higher is the level of consciousness and the whiter, the less awake and unaware of the stimuli is the person.

Figure 2.6 showcases a diagram based on the traditional consciousness model for cognitive science that is currently used for medical purposes (Laureys [2005]). This model categorizes a person depending on their LEVEL OF CONSCIOUSNESS (also known as wakefulness), and the CONTENT OF CONSCIOUSNESS (or awareness). For example, on the top right corner, very aware and very awake is a state of conscious wakefulness, while less aware and less awake is a state of deep sleep or anesthesia. Therefore, one can consider that an output from the machine to the user in these lower states is *implicit* and was *liminal* when transitioning from *explicit* during conscious wakefulness, while in the upper states of consciousness, the I/O can be both *explicit* or *implicit*.

Finally, because the users' awareness of the stimuli is in both the consciousness and the UI explicitness diagram, this framework unifies both dimensions and conceptualizes HCI in terms of the two diagrams as a three-dimensional diagram and its correspondent taxonomy (as shown in Figure 2.7 and 2.8).

2.3 A THREE-DIMENSIONAL REPRESENTATION OF HCI

This framework's main contribution is to generalize HCI using the three-dimensional diagram shown in Figure 2.7.

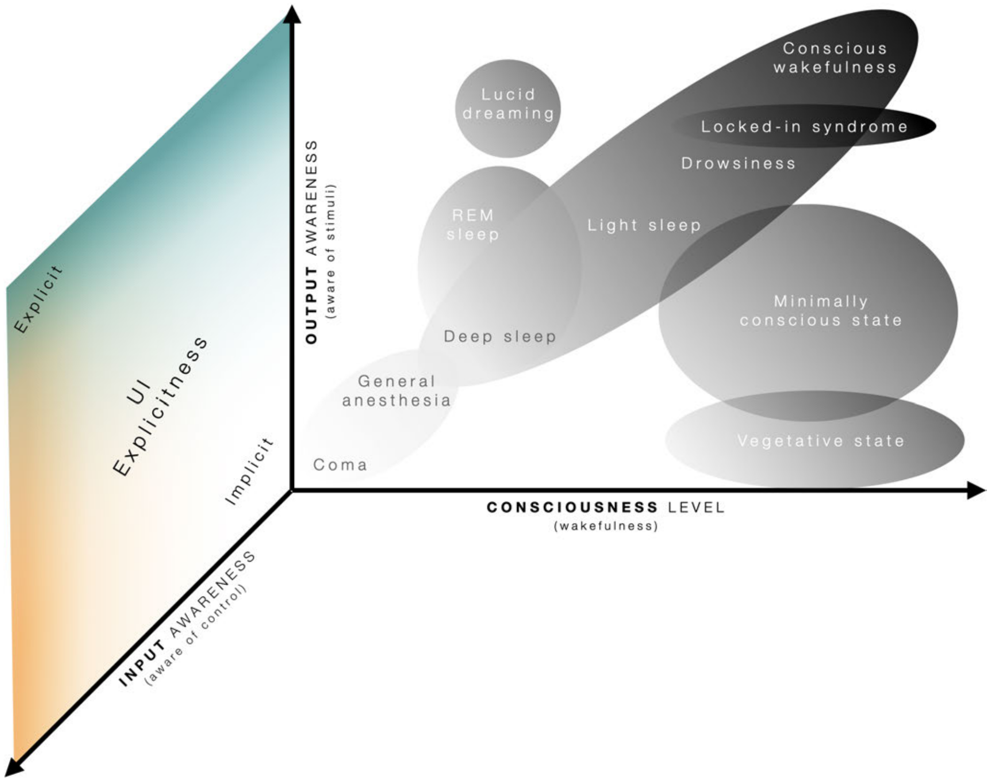

Figure 2.7: Three-dimensional representation of human-computer interactions based on *implicit/explicit* inputs and outputs, in combination with the traditional two-dimensional representation of consciousness in cognitive science. The diagram is color-coded to match Figure 2.3: the output awareness axes increase its turquoise opacity the higher is the awareness level, while the input axe increase the orange intensity. A white-ish color implies lower levels of awareness, hence the UI is *implicit*.

The three axes of our proposed framework are:

1. Output Awareness: How aware are the users of the output stimuli/feedback generated by the machine.

2. Input Awareness: How aware are the users that they are making an input to the UI.

3. Consciousness Level: How awake or aroused are the users (e.g., a person in general anesthesia is less awake than one in light sleep).

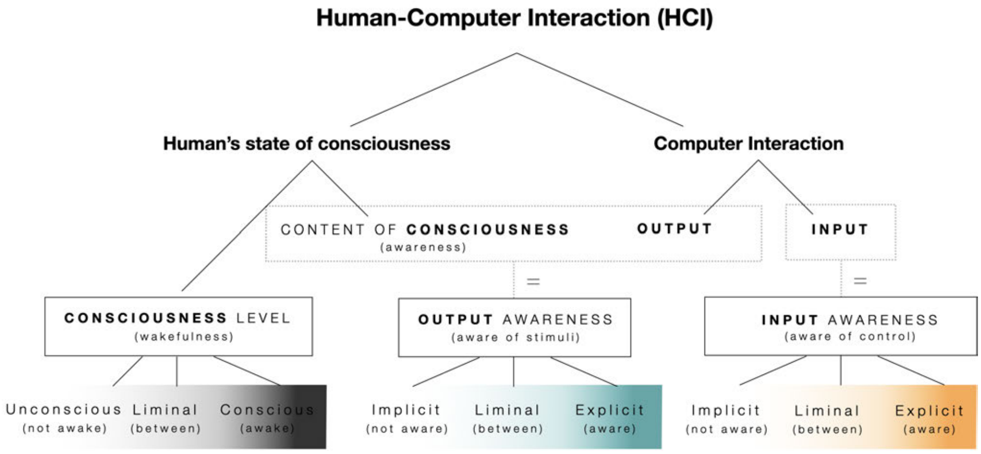

Figure 2.8: A simplified taxonomy of the three-dimensional HCI diagram presented in Figure 2.7.

By portraying user interfaces and consciousness in this three-dimensional framework, a new range of possible human-computer interactions arise. Some of these interactions might be *liminal* and, over time, evolve from one place in the 3D space diagram to another. For example, if a user starts interacting with a computer system and is unaware of any feedback until some external factor brings back their attention (hence evolving the output from *implicit* to *explicit*). Similarly, one might interact with a system before going to sleep (during conscious wakefulness), and slowly fall asleep. Hence, the user interfaces designed are *liminal*; they are transitional from one state, phase, or condition to another.

A user might start the interaction under the influence of drugs, which might initially be in a conscious wakefulness state and evolve into a drowsy-like state. In this particular example, the traditional consciousness model might categorize this mental state as "conscious wakefulness" because the user is awake and aware. However, their reality might be altered, hence even though the output of the UI remains the same (e.g., a GUI with *explicit* visual changes), their perception of the UI might be altered entirely (e.g., change of shapes or colors). The same holds for hallucinations and other altered states of consciousness that, from the perspective of the traditional consciousness model in cognitive science, are categorized as "conscious wakefulness". One could also extrapolate this to mental states over a lifetime, from the moment we are born to death, including accidents that might happen, which can lead to comatose states, general anesthesia for surgeries, or dementia.

While the science of consciousness matures and solves some of the missing gaps, this framework uses the traditional model (currently used for scientific and clinical research) and applies it to HCI. This representation might be oversimplified, as noted by researchers like Bayne et al. [2016], and more theories might evolve in the future of cognitive science and consciousness research as we gain more knowledge of how the brain works. However, this simplistic take on different "levels" of consciousness might be the most comprehensive way to investigate novel UI because it uses analogies and terms standard in HCI. For example, *implicit*/*explicit* and input/output or that the OUTPUT axis in the framework is what in consciousness research is the "content of consciousness".

2.3.1 Ethical implications and outlook

Solidly established ethics and moral compasses when developing user interfaces that interact with non-ordinary states of consciousness or using *implicit* I/O is crucial. It is incumbent on HCI researchers, engineers, and designers to be aware of potential influences when developing or using these technologies. Any implementation or research project that involves the implementation of the ideas from this framework should undergo ethical review and make sure that the benefits provided by the application outway potential harms and always receive consent and inform the user of potential implications.

Implicit HCI that track physiological signals such as heart rate or brain waves, sleep patterns, and even potential dream content should be regulated to protect the individual's privacy. Potential violations of privacy are worrisome and the danger of manipulating people's physical and mental states to serve commercial, governmental, or even criminal interests. This thesis addresses some of these challenges by developing on-device machine learning that runs on the user's phone. Most of the devices developed use BLE instead of sending the data via WiFi to a server; therefore, the data is locally stored on the user's phone. The user has control over the olfactory feedback provided at night by presetting the app's intensity and frequency. However, there are still many challenges that need to be addressed and recognized when creating or using this framework. It is not enough to note the existence of privacy challenges and ethical codes for researchers. We should also spell out the potential misuse of these technologies as with any other technologies. Therefore, we have to be extremely careful when designing these systems to prevent their misuse and always prioritize the stakeholders' wellbeing. The potential design interactions that this framework can provide by interacting with non-ordinary states of consciousness offer unique positive outcomes that otherwise might not be possible with regular UIs used during wakefulness. For example, by designing interactions to ease unconscious behaviors such as cognitive biases, phobias, or addictions, and improving the wellbeing of patients with severe brain injuries. One of the most challenging tasks facing clinicians is to differentiate vegetative states from minimally conscious states. Neuroimaging such as MRI is widely used in assessing brain damage and functional abilities, but the behavioral assessment has been the "gold standard" for detecting signs of consciousness and, thereby, determining a diagnosis. Recently, Arzi et al. [2020] found that they could discriminate between unresponsive and minimally conscious states and that if an unresponsive patient had a sniff response, this assured future regaining of consciousness. This incredible finding and much more scientific research will arise in the following years, which would greatly benefit from technological advances, for example, by monitoring breathing and automatically releasing smell in a more comfortable and miniaturized and closed-loop manner.

2.3.2 Sleep user interfaces and olfactory interfaces as an example

This thesis exemplifies some of the many possible types of UIs that could emerge by using this framework. The research presented in the following chapters explores transitional, or *liminal* UIs for wakefulness and sleep that go beyond the traditional interaction design styles (as seen in Figure 2.9).

A considerable amount of effort in HCI has been directed to make the user experience more seamless, natural, and integrated into our physical lives. However, even though we almost spend a third of our lives sleeping, user interfaces for unconsciousness have been underexplored (see Chapter 12 for further details in "Sleep User Interfaces" or "Sleep UIs"). The goal of this thesis was to explore what type of user interfaces might best influence our unconscious mind to improve our wellbeing and memory. Olfactory interfaces were chosen because of the unique characteristics of smell and the olfactory system. Unlike other modalities, olfactory stimuli can be presented during sleep without arousing the subject. Our sense of smell's anatomical structure and its privileged connection to the memory and emotional parts of the brain (amygdala and hippocampus) make olfactory interfaces an excellent candidate for wellbeing and memory-related applications. In comparison to visual, haptic, or audio interfaces, olfactory interfaces have been less explored in

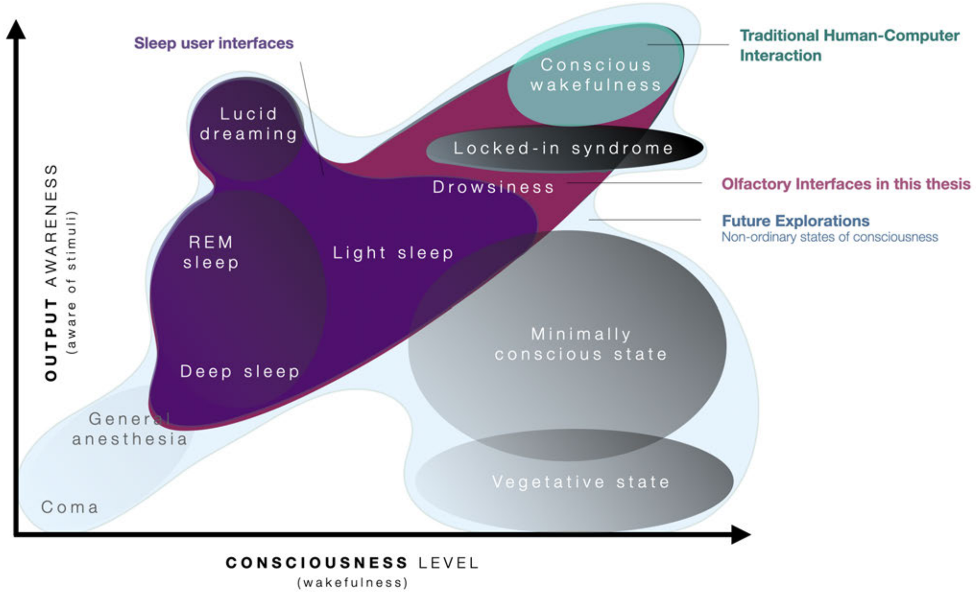

Figure 2.9: A wide array of user interfaces could be created by considering the transition between the traditional human-computer interaction during conscious wakefulness to other non-ordinary mental states like sleep.

HCI and are interesting and yet to be exploited medium that this thesis investigates. The following chapter provides a brief introduction to the history of fragrances, the physiology of the olfactory system, and the benefits of using smell for memory and wellbeing applications.