



LJMU Research Online

Fairclough, SH

A Closed-Loop Perspective on Symbiotic Human-Computer Interaction

<http://researchonline.ljmu.ac.uk/id/eprint/2237/>

Article

Citation (please note it is advisable to refer to the publisher's version if you intend to cite from this work)

Fairclough, SH (2015) A Closed-Loop Perspective on Symbiotic Human-Computer Interaction. Lecture Notes in Computer Science, 9359. pp. 57-67. ISSN 0302-9743

LJMU has developed **LJMU Research Online** for users to access the research output of the University more effectively. Copyright © and Moral Rights for the papers on this site are retained by the individual authors and/or other copyright owners. Users may download and/or print one copy of any article(s) in LJMU Research Online to facilitate their private study or for non-commercial research. You may not engage in further distribution of the material or use it for any profit-making activities or any commercial gain.

The version presented here may differ from the published version or from the version of the record. Please see the repository URL above for details on accessing the published version and note that access may require a subscription.

For more information please contact researchonline@ljmu.ac.uk

<http://researchonline.ljmu.ac.uk/>

A CLOSED-LOOP PERSPECTIVE ON HUMAN-COMPUTER SYMBIOSIS: IMPLICATIONS OF MACHINES WITH AN AGENDA

Stephen Fairclough,
Liverpool John Moores University,
UK.

Abstract

This paper is concerned with how people interact with an emergent form of technology that is capable of both monitoring and affecting the psychology and behaviour of the user. The current relationship between people and computer is characterised as asymmetrical and static. The closed-loop dynamic of physiological computing systems is used as an example of a symmetrical and symbiotic HCI, where the central nervous system of the user and an adaptive software controller are engaged in constant dialogue. This emergent technology offers several benefits such as: intelligent adaptation, a capacity to learn and an ability to personalise software to the individual. This paper argues that such benefits can only be obtained at the cost of a strategic reconfiguration of the relationship between people and technology - specifically users must cede a degree of control over their interaction with technology in order to create an interaction that is active, dynamic and capable of responding in a stochastic fashion. The capacity of the system to successfully translate human goals and values into adaptive responses that are appropriate and effective at the interface represents a particular challenge. It is concluded that technology can develop lifelike qualities (e.g. complexity, sentience, freedom) through sustained and symbiotic interaction with human beings. However, there are a number of risks associated with this strategy as interaction with this category of technology can subvert skills, self-knowledge and the autonomy of human user.

Keywords: Symbiosis, Physiological Computing, Intelligent Adaptation

1. Introduction

The last three decades have seen huge innovation with respect to how we interact with computers. Communication via command lines was succeeded by WIMP interfaces and natural modes of communication via gestures and speeches are currently common features of desktop technology. Brain-computer interfaces represent the next frontier in human-computer interaction (HCI), where the neurological foundation of perception and action are utilised directly as a form of input control. Despite advances with respect to the available forms of input control, the basic communication dynamic of the human-computer dyad remains curiously fixed - the human 'speaks' and the computer 'listens and obeys.' Technology inhabits the passive role of slave-system that responds rigidly to a steady stream of directives from a human master, who directs actions towards a desired goal.

The distinction between the active role of the user and the passive function of the machine is starkly defined by the rigid turn-taking structure of contemporary HCI. This flow of information between person and machine has been depicted as two monologues rather than a genuine dialogue [1]. The way in which people interact with technology has also been described as asymmetrical with respect to the flow of information [2]. In other words, the person is free to interrogate the operational state of the computer (e.g. memory usage, Wi-Fi speed etc.) whereas the latter remains essentially blind to the psychological status of its user. By contrast, when technologies communicate with one another, information exchange can be symmetrical because each entity may freely probe and cross-examine all operational aspects of the other. The asymmetry that characterises interaction between humans and computers is distinguished by the absence of awareness on the part of the machine, which relegates a technological agent to the role of a passive and inert participant. In the absence of any ability to perceive or interpret the inner world of the user, the computer has minimal capacity for inference, anticipation, learning or any other quality that would liberate technology from its role as a slave-system.

The evolution of symmetrical forms of HCI are key to the creation of 'smart' technologies, which possess autonomy and intelligent adaptation [1]. This development should be considered within a general context of symbiosis between people and technology. Symbiosis may be described simply as two unlike organisms "living together" [3] in a relationship that may be mutualistic (i.e. both parties benefit), commensalistic (i.e. one benefits but the other is neither harmed or helped), or parasitic (i.e. one benefits with harm inflicted on the other).

If we define technology in the broadest sense, from the humble pencil to a nuclear power station [4], there are obvious benefits of technological forms for humanity as a species. Technology extends and augments our human limitations, a shovel allows the person to dig more effectively and efficiently, the motor car offers greater speed of transportation than travelling by foot [5]. Binoculars, telescopes and microscopes extend the range of visual perception and create a flexible, orthotic range [6] for human senses that greatly exceeds our "natural" limitations. The emergence of mobile devices combined with Internet connectivity and enhanced data storage augment our finite cognitive capabilities with respect to the storage and retrieval of information [7]. All these enhancements are achieved by "redistributing" task or information-processing demands between the human being and technological aids. It has been argued that the human brain has two important qualities that forge and fortify reliance on technology [8]. The brain is opportunistic in that it seeks to invent technological tools wherever there is potential for a significant improvement of efficiency and effectiveness. The brain is also a malleable organ, capable of co-opting technological tools seamlessly into existing behaviour and representations of self - and then creating a second and even third layers of tools to further bolster our human efficiency and effectiveness [5].

The relationship between symbiotic species may be described as obligate or facultative [9]. The former describes a state of co-dependence where each entity depends entirely upon the other for its continued survival. A facultative relationship represents those instances where two species can but not obliged to live together in order to survive. Whilst humans are currently the primary creators of technology, it would be a mistake to regard our relationship with technology as anything but an obligate form of mutualism. Individuals may attempt to (unsuccessfully) relinquish technological tools (see [5] Ch. 10), but technology is so entwined with human existence that any attempt to live without technological aids would force the human recipient to endure the kind of harsh living conditions that characterised feudal life 800 years ago [6]. It is also doubtful whether humans would be even capable of eradicating technology from our world if one considers the logistic barriers to that ill-advised endeavour [5]. Hence, we find ourselves in the contradictory position of being both master and slave to technology [5]. Rather than bemoaning our collective dependency on gadgets and computers, perhaps the most realistic course of action is to embrace this obligate relationship to further exploit human symbiosis with machines, as we have already been doing for several centuries. In the words of Hancock [6]: "Our ecology is technology. If we are to achieve our individual and collective goals, it will be through technology." (p. 66).

Our relationship with technology as a species is constructed upon an obligate form of symbiosis where humans rely on machines to extend our senses and capabilities - and technologies depend on human need and ingenuity in order to provide them with form and function. Despite this inter-dependence, the way in which we interact with machines remains asymmetrical with autonomy within HCI residing purely with the human user. This paper will outline the potential of physiological computing to both facilitate symmetrical forms of HCI and enhance our symbiotic relationship with technological systems. If technology can develop in this direction, the relationship between users and machines evolves towards a close, collaborative interaction that has profound implications for future technologies and its human users.

2. A Closed-Loop Perspective on Human-Machine Symbiosis

Human-machine symbiosis can describe the relationship between machine and person that occurs within a shared space or task [10]. A recent review defined human-machine symbiosis in terms of a computer that was capable of both monitoring and affecting the cognitions, emotions and behaviours of the user [11]. This description is identical to the closed-loop logic of physiological computing systems [12, 13] where signals from the

brain and body of the user are converted to control inputs in order to facilitate intelligent adaptation at the interface. Physiological computing systems are constructed around a biocybernetic loop [14] where data from brain activity and the autonomic nervous system are collected, analysed and classified for input into an adaptive controller, which triggers actions at the interface.

2.1 Monitoring the User

Data from the brain and body are particularly appropriate for monitoring the psychological state of the user; in addition, these data have the advantages of being: quantifiable, continuously available, sensitive to unconscious activity and implicit, i.e. no overt response is required from the user [15]. In the case of physiological computing, the dynamic state of the user is inferred on the basis of spontaneous activity from the brain and the body [13, 16]. Analyses of these data yield a digital and quantified representation of the user state, which is made constantly available to the system. It is important to note that this representation of the user state is achieved via analogy as opposed to a literal re-representation of embodied experience [17]. The first step towards human-computer symbiosis is a simplification and quantification of embodied human experience into sparse information patterns that are digestible and reconcilable with a closed-loop mechanism of control and communication [18]. This act of abstraction is necessary in order to integrate the dynamic psychological state of the user within a cybernetic control loop.

There is a peculiar duality to this digital representation of self that acts as a point of origin within the biocybernetic loop. Whilst data from the brain and body are not a literal representation of the self or experience, they are derived from activity within the central nervous system and evoke both a degree of identification and biophilia [19], i.e. a preference for living systems. On the other hand, this quantified representation of self simultaneously evokes a technophilic proclivity for tools and technologies [5] and a reflexive perspective on self, i.e. the person becomes “an observing system observing itself observing” [17] (p. 144). By endowing a symbiotic computing system with the capacity to both monitor and represent the user, the loop creates a contradictory entity that (from a human perspective) is both self and other - the data are representative of the self but viewed from the objective perspective of another. It is important that users are fully informed in this respect. In other words, the measures upon which the quantification of state ought to be clearly defined and the user deserves a degree of education about the sensitivity and fallibility of this process. The user should understand that the process of measurement is neither perfectly sensitive nor absolutely representative due to the inherent limitations of measuring brain and body outside of the laboratory. This is important because users should not harbour unrealistic expectations about the fidelity of this representation or degree of personal insight that may be obtained via interaction with a biocybernetic system.

The capacity to monitor the user is the first challenge for symmetrical HCI, the next question is how the closed-loop mechanism should work with that user representation in order to create intelligent adaptation at the interface.

2.2 The Machine With An Agenda

The adaptive controller is the core element within the biocybernetic loop. This component receives information about the state of the user and translates these data into a range of appropriate responses at the interface. The adaptive controller encompasses a set of rules to describe how target state a is linked to an adaptive response x at the interface; for fuller technical description, see [16].

Aside from its technical substance, the adaptive component represents the means by which the system exerts a specific influence on the state or behaviour of the user. A number of biocybernetic loops have been created to serve different application domains, from mental workload classification [20], affective computing [21] and entertainment [22] to attention training [23]. In each case, the closed-loop model requires a target state to be defined and adaptations at the interface are designed to either induce/sustain a ‘desirable’ target state or reduce/ameliorate any target state deemed to be “undesirable.”

For mental workload monitoring, the loop is designed to sustain a moderate level of mental workload and to avoid instances of high workload in order to preserve performance and safety. An affective computing system may be designed to detect a

negative emotional state, such as frustration, and to trigger adaptive responses at the interfaces designed to reduce this emotion. An adaptive computer game would adjust gaming parameters in real-time to avoid the player becoming bored or disengaged. The definition of a psychological state to be achieved or avoided is common theme to all closed loop systems, and is especially relevant to symbiotic systems.

The closed loop system is governed by goal-directed logic. Unlike the inert and passive technology of today, this symmetrical interaction is characterised by a degree of agency on the part of the machine and a requirement for the human to cede a degree of control to the system. A user can decide whether or not to engage with the technology, but once the interaction has been initiated, the system can respond in a stochastic (as opposed to a deterministic) fashion. This is a small but significant shift in the relationship between people and computers.

Given that symmetrical HCI requires the human to relinquish a degree of control over the interaction, it is important to define the agenda of the machine to be effective, reliable and not lead to unforeseen circumstances. The introduction of agency or intentionality on the part of a machine shifts attention from the 'how' to the 'why' of technology because "the quintessential bottom line is that technology must be used to enfranchise not to enslave." [6] (p.60). A closed loop system with intentionality must be used to materialise human goals and human values [24].

The formulation of human values within the closed-loop system remains a significant challenge. Illich [24] forwarded the case for convivial tools as technologies that create an opportunity for users to enhance and enrich the contribution of autonomous individuals. But how to recast this vague notion of conviviality within the precise semantics that are required by an adaptive controller within closed-loop control? In the first instance, a directive to promote engagement during an adaptive game may have unintended negative side effects for the player, e.g. spend too long playing the game, suffer from fatigue and sleeplessness. Even if these caveats are captured within the rules of the system, there are other hurdles to be faced with respect to materialisation of goals and values. Precise definition of goals and values may differ enormously between different members of the user population. In addition, there may be a number of stakeholders aside from the user who are directly or indirectly affected by the directives of the system, e.g. user's line manager & colleagues, user's family, system designer, corporation who supplied technology etc. There is also the potential for ambiguity or conflict because the definition of a goal for the loop may differ at the levels of individual, society and nation [6]. For example, a closed-loop system designed to improve productivity in a company could enfranchise the board of directors whilst enslaving their employees. It may be unrealistic to expect technology to encompass convivial goals per se, but rather we should seek to build conviviality into technological tools by carefully defining the context and operating conditions under which technology is used [5].

The use of technology to explicitly enshrine and define our human values presents a number of significant challenges, as well as considerable opportunities to use technology as a vehicle to enshrine and develop a humanist agenda - in the words of Arthur [4] "we trust in nature but we hope in technology" (p. 246).

4. First- and Second-Order Adaptation

The biocybernetic loop encompasses a process of monitoring the user and translating those data into intelligent adaptation at the interface. This procedure requires a set of rules whereby target state a triggers adaptive response x , however, this relationship is not an exclusive and there may be a range of potential responses that are appropriate once a specific target state has been recognised by the system. A detection of frustration could trigger an offer of help or the suggestion of a rest break or an alteration of current music to a calming playlist. The rules that translate detection into an adaptive response may draw from a repertoire of possibilities, all of which could conceivably result in a desired effect on the user. In addition, some users may favour certain categories of adaptive response from the repertoire over others.

It is the convention to think of closed-loop systems in terms of one discrete cycle of monitoring and adaptation. In this case, a single cycle may describe how the detection of frustration is translated into the appearance of help information at the interface. This is a first-order process of adaptation wherein the loop detects and responds to a target state in

the short-term. Once this adaptation has been activated, it is possible for the system to detect those changes in user state, which occur as a direct consequence of that adaptive response. If help is offered in order to alleviate frustration, the continual process of monitoring will indicate whether this response successfully achieved its goal. If no such change occurs, or if frustration actually increased, the adaptive controller must select a different response from its repertoire, such as selecting a playlist of calming music. Once the calming music has been activated for a short period, the system can perform a third check to assess whether frustration has been alleviated as expected. This process is called second-order adaptation or reflexive adaptation [25] because the loop monitors the consequences of its own intervention on the state of the user. This second-order level of adaptation fulfills two functions, it is a self-check (that the original adaptive response was effective) and represents an opportunity for a closed-loop system to collate information about user preferences based a long-term process of repeated interaction.

It is easy to understand how this second-order process of adaptation can facilitate machine learning over a sustained period of use. In order for the system to function, it must accumulate a database that describes those adaptive responses found to be effective for a particular user and those that are not. Therefore, the system is installed and initiated with a large number of potential adaptations, and through a process of sustained interaction coupled with second-order processing, all items in the adaptive repertoire are tagged with a value, which directly affects the probability of selection for that specific user. Second-order adaptation describes a generative process of individualisation where software is customised on the basis of its repeated interactions with a particular user. Second-order adaptation also represents a level of human-machine symbiosis where the technology is able to learn about the effects of its own actions.

The evolving lifecycle of this reflexive technology has been described as a process of mutual adaptation with three main phases [25, 26]. The initial encounters between the adaptive system and the user are characterised by a process of *improvisation*. The system responds to the user in a generic fashion using default adaptations with no prior knowledge of individual preferences. Adaptation may be perceived by the user to be erratic and occasionally inappropriate. As the user spends more time interacting with the system, second-order adaptation should improve the timeliness and quality of the responses made by the system. This second phase of *reciprocal coupling* is characterised by enhanced performance as the adaptive repertoire of the system is tailored to the individual. This is the phase wherein the system constructs a stable model of user preferences based on repeated interactions. If we look further ahead in time, in terms of years and decades, it is reasonable to expect that any stable model of preferences will have limited longevity as the user acquires higher levels of skill or habituates to popular responses or experiences cognitive changes due to ageing. The third phase of *co-evolution* describes a process of updating the existing model of user preferences as the system adjusts to long-term changes over several years. This cycle of monitoring, adaptation and reflexive adaptation represents perhaps the ultimate expression of user-centred software design.

A process of reflexive adaptation may also have some bearing on the problem of formalising convivial goals within a technological system described in the previous section. These difficulties were recognised over fifty years ago by Norbert Wiener [27]; his solution was to build cycles of self-correction into the loop by inserting regular interventions from a human arbitrator within the learning process of the cybernetic loop. This strategy was suggested as a safeguard to ensure that the actions of the machine did not significantly depart from the preferences and values of the human being. The capacity of the biocybernetic loop to interact with the human central nervous system continuously and over a sustained period of time captures the essence of this idea - provided that implicit data from the brain and body are sufficiently nuanced to intercede on behalf of the person; however, there are concerns about the test-retest reliability of psychophysiological measures in the field [28]. For this strategy to act as a proxy for the human arbitrator, much depends on the sensitivity and reliability of the data used to represent the user, if these data are inconsistent then the possibilities for machine learning in the long-term are fundamentally compromised.

5. Technology for Life

The development of symmetrical HCI via the biocybernetic loop reconfigures the relationship between people and computers. Our earlier characterisation where the human “speaks” and the computer “listens” remains relevant, but with the additional caveat that the computer can now “speak back.” This machine with an agenda is active and dynamic as opposed to the passive and static technologies that we currently use on a daily basis. A nascent form of closed-loop control offers the prospect of smart technology, capable of intelligent adaptation and personalisation, but at the price of subverted human autonomy. This change does not mean simply that the traditional roles of human and machine are recomposed, by converting the user into a pattern of information that is *operated upon* within a closed-loop, the loop obscures the boundary between human and computer. Within this conception, human and machine function as a single “cooperative intelligent entity” [29] - a cybernetic organism that is capable of learning based on previous interaction to create a flexible repertoire of adaptive responses.

We have already described how technology can supplement our human capacities and capabilities. Consider the inverse of that position - how can humans develop the capacities, proficiencies and potential of technology? According to Kelly [5], the developmental trajectory of technology is characterised by universal tendencies towards: complexity, diversity, freedom, mutualism, sentience and evolvability. These inclinations are accelerated by the concepts described in this paper. The closed-loop logic of symmetrical HCI requires the additional complexity of monitoring and representing the human user. The capacity of the loop to facilitate learning in the longer-term creates the potential for greater diversity within the same piece of software, i.e. software co-evolves with the individual user, begetting a generative process where different patterns of development are possible within the same technology. The loop is a machine with an agenda and this agenda imbues technology with the freedom to make mistakes and to learn from those mistakes in order to make better choices in future. The loop is a human-machine hybrid that deepens the degree of cooperation, dependency and mutualism between person and computer. The process of second-order adaptation permits technology to reflect on the effects of its own actions, thus creating a rudimentary form of sentience. Most importantly, the process of monitoring and adaptation allows technology to develop advanced capabilities by learning directly from repeated interaction with human users. Several authors have described a process of bootstrapping [5, 8] whereby humans supplement their skills and capabilities via technology, we may now contemplate a future where closed-loop technology uses sustained interaction with people as an engine to boost capabilities and accelerate its own evolutionary development.

One hopes that such exciting and provocative developments occur in a convivial spirit, thus maximising the potential and possibilities for all human life. However, living so closely with technology has the potential to create several significant problems for our species. There is the obvious issue of control or rather uncontrollability when a person submits to interaction with technology within a closed-loop. By relinquishing total control over technology, there is the potential to undermine human agency; in the words of Wiener [18]: “When human atoms are knit into an organisation in which they are used, not in their full rights as responsible human beings, but as cogs and levers and rods, it matters little that their raw material is flesh and blood” (p. 185). There is also the problem of data privacy, intrusion and misrepresentation via the process of monitoring within the loop [30]. It has already been emphasised that representation of self within the loop is an analogous creation rather than a literal re-representation of thoughts, moods and experiences. The act of interacting with this analogous representation, which is both self and other, has the potential to simultaneously alienate the individual and could even create feelings of disembodiment [8]. Like all systems that automate or semi-automate, symmetrical HCI has the potential to de-skill the individual [31], whether that person is driving a car or playing a computer game.

The long-term relationship between humanity and technology has been characterised as an infinite game [5] and the purpose of an infinite game is not to win but to keep playing. The burgeoning complexity of our relationship with machines emphasises how any attempt to sustain human beings in the sovereign position of a master who retains ultimate control over his technological creation are doomed to failure [6]. We must

explore new trajectories of interaction with technology, which maximises opportunities for both humans and machines as a single intelligent cooperative entity.

6. Summary

Our historical relationship with technology has been characterised by the use of tools being used to extend human capabilities and capacities. We are currently entering a period where symmetrical HCI via physiological computing will lead to greater mutualism between people and computers. It is argued that emerging technology will demonstrate greater intelligence during interactions with people by monitoring and affecting user psychology. In addition, these 'smart' technologies will be capable of anticipating the needs of the individual and personalising responses; they will respond in an active and stochastic pattern. In order to reap these benefits, humans must submit themselves to implicit monitoring by technology, allow complex and embodied internal states to be reduced to sparse, analogous representations, and cede a degree of control to the computer.

The challenge for designers of this emergent technology is to enable this transition in a convivial fashion to:

1. Ensure that human user can disable the adaptive process at any time
2. Ensure that human user can manually edit (i.e. enable/disable) the repertoire of adaptive responses
3. To carefully formulate adaptive responses from the system that are compatible with the goals and values of the user
4. To use second-order monitoring to ensure that adaptive responses are desirable from the perspective of the user
5. Educate users with respect to the internal logic of the system in order for engender trust in the technology via enhanced understanding [32]

If these compromises can be made in a convivial fashion, machines can be permitted to learn from regular interaction with the individual in order to customise responses to the preferences of the individual. The creation of an intelligent, cooperative entity, which arises from close coupling between human or machine, will increase benefits and opportunities for both parties.

7. References

1. Norman, D.A., *The Design of Future Things*. 2007, New York: Basic Books.
2. Hettinger, L.J., et al., Neuroadaptive technologies: applying neuroergonomics to the design of advanced interfaces. *Theoretical Issues in Ergonomic Science*, 2003. 4(1-2): p. 220-237.
3. Martin, B.D. and E. Schwab, Current usage of symbiosis and associated terminology. *International Journal of Biology*, 2013. 5(1): p. 32-42.
4. Arthur, W.B., *The Nature of Technology: What It Is and How It Evolves*. 2009: Penguin.
5. Kelly, K., *What Technology Wants*. 2010: Penguin.
6. Hancock, P.A., *Mind, Machine and Morality: Towards a Philosophy of Human-Technology Symbiosis*. 2009: Ashgate.
7. Clark, A. and D.J. Chalmers, The extended mind. *Analysis*, 1998. 58: p. 10-28.
8. Clark, A., *Natural-Born Cyborgs: Minds, Technologies, and the Future of Human Intelligence*. 2003: Oxford University Press.
9. Douglas, A.E., *The Symbiotic Habit*. 2010, New Jersey: Princeton University Press.
10. Licklider, J.C.R., Man-Computer Symbiosis. *IRE Transactions on Human Factors in Electronics*, 1960. HFE-1: p. 4-11.

11. Jacucci, G., et al., Symbiotic Interaction: A Critical Definition and Comparison to other Human-Computer Paradigms, in *Symbiotic Interaction*, G. Jacucci, et al., Editors. 2014, Springer International Publishing. p. 3-20.
12. Allanson, J. and S.H. Fairclough, A research agenda for physiological computing. *Interacting With Computers*, 2004. 16: p. 857-878.
13. Fairclough, S.H., *Fundamentals of Physiological Computing*. *Interacting With Computers*, 2009. 21: p. 133-145.
14. Pope, A.T., E.H. Bogart, and D.S. Bartolome, Biocybernetic system evaluates indices of operator engagement in automated task. *Biological Psychology*, 1995. 40: p. 187-195.
15. Byrne, E. and R. Parasuraman, Psychophysiology and adaptive automation. *Biological Psychology*, 1996(42): p. 249-268.
16. Fairclough, S.H. and K. Gilleade, Construction of the biocybernetic loop: a case study, in *14th ACM International Conference on Multimodal Interaction*. 2012, ACM: Santa Monica. p. 571-578.
17. Haynes, N.K., *How We Became Post Human: Virtual Bodies in Cybernetics, Literature and Informatics*. 1999: University of Chicago Press.
18. Wiener, N., *The Human Use Of Human Beings: Cybernetics & Society*. 1954, Boston: Da Capo Press.
19. Wilson, E.O., *Biophilia*. 1984, Cambridge: Harvard University Press.
20. Wilson, G.F., Pilot workload, operator functional state and adaptive aiding, in *Operator Functional State: The Assessment and Prediction of Human Performance Degradation in Complex Tasks*, G.R.J. Hockey, A.W.K. Gaillard, and O. Burov, Editors. 2003, ISO Press: Amsterdam. p. 194-203.
21. Kapoor, A., W. Burleson, and R.W. Picard, Automatic prediction of frustration. *International Journal of Human-Computer Studies*, 2007. 65: p. 724-736.
22. Dekker, A. and E. Champion. Please biofeed the zombies: enhancing the gameplay and display of a horror game using biofeedback. in *DiGRA*. 2007.
23. Mishra, J. and A. Gazzaley, Closed-loop cognition: the next frontier arrives. *Trends Cogn Sci*, 2015. 19(5): p. 242-3.
24. Illich, I., *Tools For Conviviality*. 1973, New York: Harper and Row.
25. Serbedzija, N. and S.H. Fairclough, Reflective pervasive systems. *ACM Transactions on Autonomous and Adaptive Systems*, 2012. 7(1).
26. Serbedzija, N. and S.H. Fairclough, Biocybernetic loops: from awareness to evolution, in *IEEE Congress on Evolutionary Computation*. 2009: Trondheim, Norway.
27. Wiener, N., *God and Golem Inc*. 1964, Cambridge, Mass: MIT Press.
28. Tomarken, A.J., A psychometric perspective on psychophysiological measures. *Psychological Assessment*, 1995. 7(3): p. 387-395.
29. Rahimi, M. and P.A. Hancock, Optimization of hybrid production systems: the integration of robots into human-occupied work environments, in *Human Factors in Organizational Design and Management - II*, O. Brown and H.W. Hendricks, Editors. 1986, Elsevier: North-Holland. p. 39-54.
30. Fairclough, S.H., Physiological data should remain confidential. *Nature*, 2014. 505: p. 263.
31. Parasuraman, R. and V. Riley, Humans and automation: use, misuse, disuse, abuse. *Human Factors*, 1997. 39: p. 230-253.
32. Miller, C.A. Trust in adaptive automation: the role of etiquette in tuning trust via analogic and affective methods. in *First International Conference on Augmented Cognition*. 2005. Las Vegas, NV.