On the Biology of Technostress: Literature Review and Research Agenda

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Abstract

Despite the fact that human society has greatly benefited from the availability of information and communication technologies (ICT), both the use and ubiquity of ICT may also have a "dark side." Direct human interaction with ICT, as well as perceptions, emotions, and thoughts regarding the implementation of ICT in organizations and its pervasiveness in society in general, may lead to notable stress perceptions—a type of stress referred to as technostress. Analysis of the information systems (IS) literature reveals that technostress has hardly been addressed from a biological perspective. This is problematic, because biology not only provides objective measurements, but also, to a notable degree, determines human behavior toward ICT. Most important, biological measures (e.g., stress hormone levels, cardiovascular activity) are crucial predictors of human health, making them an indispensable complement to self-reports on stress perceptions. Against this background, the present article reviews the technostress research based on biological approaches that has been published in various disciplines such as human-computer interaction, medicine, biological psychology, and ergonomics. With the goal of developing a "big-picture" view of technostress and biology, this article integrates a body of highly fragmented work. The review reveals significant negative biological effects that develop from human interaction with ICT (e.g., increased activity of the cardiovascular system, or elevated levels of stress hormones such as adrenaline and cortisol). However, the review also indicates that countermeasures, which may positively affect biological parameters (e.g., reduced levels of stress hormones), do exist. Drawing on the literature review, this article also specifies a research agenda for future technostress research. The agenda is organized along three themes (theory and methods, design science and engineering, health and coping strategies), and proposes fifteen research questions (topics) that can be addressed in future investigations.

Keywords: Adrenaline, Biology, Blood Pressure, Brain, Computer, Computerstress, Cortisol, Internet, Genetics, Heart Rate Variability, Hormone, HPA Axis, Internet, Noradrenaline, Technostress, Skin Conductance, Stress, Information Technology

ACM Categories: K.4, K.6

General Terms: Design, Management, Measurement, Theory

Acknowledgment

I would like to thank Henri Barki, member of the preeminent editorial board of the *DATA BASE for Advances in Information Systems*, for his thoughtful comments on an earlier version of the manuscript. Moreover, I would like to thank three anonymous reviewers for their excellent work in providing guidance on ways to improve the paper. Also, I appreciate the support of the University of Linz, International Office, and the Tech3Lab at HEC Montréal, which supported a visiting professorship at HEC Montréal in spring 2012. Also, I am grateful to the Department of Information Technologies at HEC Montréal, which provided support and an inspiring academic environment during my visiting professorship. Finally, I would like to thank Deborah C. Nester for proof-reading.

Technology: Friend *and* Foe

The market research firm Gartner (www.gartner.com) recently announced that the worldwide enterprise software market had grown to $245 billion in 2010, with Microsoft ($55 b.), IBM ($25 b.), Oracle ($24 b.), and SAP ($13 b.) as the top four vendors. Moreover, as of 2011, 0.7 billion of the 1.8 billion households worldwide have a personal computer, and 0.6 billion have Internet access, according to reports by Internet World Stats (www.internetworldstats.com) and the International Telecommunication Union (www.itu.int). Moreover, these two institutions indicate further impressive numbers, including the facts that of the 7 billion people worldwide, nearly 2.3 billion use the Internet, and that there are currently almost 6 billion mobile-cellular subscriptions and 1.2 billion mobile Web users. These statistics demonstrate the definitive impact of Information and Communication Technologies (ICT) on humans today, both in organizational and private contexts.

Individuals, organizations, and society in general have gained significant benefits through the use of ICT—including examples such as extensive possibilities for communication, increased and rapid access to information, improvements in performance, as well as productivity enhancements (e.g., Brynjolfsson & Hitt, 2000; Melville et al., 2004).

Despite this positive impact, however, ICT may also have a "dark side." Specifically, direct human interaction with ICT, as well as perceptions, emotions, and thoughts regarding the implementation of ICT in organizations and its general ubiquity in society, may lead to notable stress perceptions. This type of stress is referred to as *technostress* (Weil & Rosen, 1997).

The psychologist Craig Brod coined this term in the 1980s (Brod, 1982). In his book *Technostress: The Human Cost of the Computer Revolution*, Brod defines technostress as "a modern disease of adaptation caused by an inability to cope with the new computer technologies in a healthy manner," pointing out that it manifests itself, particularly, in "the struggle to accept computer technology" (Brod, 1984, p. 16). One year later, *Nature*, one of the most prestigious scientific journals worldwide, reported in its news section that "[t]echnostress is the stress and concomitant psychosomatic disorder induced by the introduction of high technology. Usually high technology means office automation [and] it is hoped that environments that minimize stress can be designed" (Anderson, 1985, p. 6).

These and similar contributions to the field of study in the 1980s (e.g., Elder et al., 1987) have initiated a number of corresponding investigations, one of which achieved attention and popularity similar to that of the original work by Brod (1984), namely psychologists Michelle Weil and Larry Rosen's book *Technostress: Coping with Technology @Work @Home @Play*.[1] In this book, technostress is defined as "any negative impact on attitudes, thoughts, behaviors, or body physiology that is caused either directly or indirectly by technology" (Weil & Rosen, 1997, p. 5).

To sum up, the definitions in these pioneering works indicate that technostress is both a psychological *and* a biological phenomenon, and that it plays a key role in both organizational and private contexts.

A thorough analysis of the literature, however, reveals that the phenomenon has hardly been addressed from a biological perspective by different scientific disciplines, particularly in information systems (IS) research. This is problematic, because biology not only provides objective measurements, but also, to a large extent, determines health, as well as behavior (e.g., Cacioppo et al., 2000). Consequently, ignoring the biological level of analysis would mean disregarding an important measurement approach, as well as a crucial antecedent of both health and ICT behavior, and this, in turn, may significantly impede progress in the IS discipline.

Generally, biology investigates *life and living organisms*. Because IS research is concerned with the development, use, and impact of ICT, which implies that *humans* and their interaction with ICT is at the core of the discipline, it is evident that biology can constitute a major reference discipline for the IS field.

Importantly, before humans even begin to consciously perceive negative effects of stress (e.g., fatigue perceptions), about which they could give an introspective account in self-reports, it is often the case that biological systems (e.g., stress hormones) have already started to act in the body, thereby negatively affecting health. In other words, once humans start to consciously perceive negative effects of stress, serious damage might have already occurred. As such, the implication for IS studies is that whenever technostress is investigated, the complementary investigation of biological parameters is critical for a valid measurement of the phenomenon. Because several stress hormones can be measured based on salivary assessments (rather than blood samples), the measurement of stress hormones is an easily realizable field of activity in IS research.

[1] The Brod book (1984) had 346 citations as of March 22, 2012, at *Google Scholar*, and Weil and Rosen (1997) had 124 citations. The average number of annual citations are approximately 12 for Brod (1984) and 8 for Weil and Rosen (1997) (Source: Harzing's Publish or Perish Author Impact Analysis, March 2012).

Despite the fact that there exists a research deficit in the IS discipline, the present paper's literature review also revealed that other fields (mainly human-computer interaction, ergonomics, biological psychology, and medicine) have already contributed to the investigation of technostress from a biological perspective. Despite the contributions of this research, however, these works constitute a body of *highly fragmented work*. Hence, a cumulative research tradition does not exist in the field of technostress.

Against such a research background, this article provides an integrative review of the literature on the biology of technostress. The biological perspective is in line with recent calls for consideration of neurobiological approaches in IS research (e.g., Dimoka et al. 2011, 2012; Riedl, 2009; Riedl et al., 2010a). Importantly, because the findings reported in the existing literature substantiate the significant biological effects of technostress, the present paper is of paramount relevance for theory, management, health policy, and engineering.

The remainder of the paper is structured as follows. In the next two sections, both the objectives and the roadmap of this article are outlined in detail. (The methodology of the search for technostress literature is described in the Appendix.) After the foundational objectives and the roadmap, the paper presents a discussion of related works on technostress from the IS discipline, with a focus on peer-reviewed journal articles. The intent of this section is to show the status of current IS research on technostress. In essence, IS studies have relied solely on perceptual measures, which makes a strong case supporting the need for biological approaches in IS research. Nonetheless, following a cumulative research tradition, the existing IS literature offers a complementary basis for future biological studies. Next, the paper details the biological foundations of stress, thereby developing the conceptual basis for the article's primary section— the review of the identified biological investigations into technostress. Finally, the review findings provide the foundation for an outline of possible avenues for future research, framed as a research agenda that includes fifteen research questions (topics), and these are followed by the paper's concluding comments.

Objectives of this Article

Despite the fact that IS research has not so far contributed to biological investigations of technostress in the form of peer-reviewed journal publications (except for one article by Riedl et al., 2012), the need for this type of study is well documented, as expressed by leading authorities in the field (e.g., Dennis Galletta or Varun Grover). Importantly, this need is based on the notion that technostress investigations are incomplete without consideration of biological approaches. Galletta and colleagues, for example, wrote in 1993 that "[o]ne of the key limitations to [a technostress study] is the lack of actual measures of stress rather than subjective self-evaluation [and there] are a number of possible measures of physiological stress such as heart rate, skin temperature, skin resistance, and cortisol secretion" (Huston et al., 1993, pp. 78, 80). Similarly, in a more recent technostress paper Grover and colleagues highlight that "[e]xploring the unintended consequences of ICT use on physiological symptoms is another fruitful research avenue" (Ayyagari et al., 2011, p. 852).

Considering (a) the significant research deficit in biological technostress investigations in the IS literature, (b) the great interest in this topic within the IS community (and probably also in several other behavioral disciplines), and (c) the available, but highly fragmented literature that is published in outlets across various scientific fields, the present article has two major objectives:

- To provide a tutorial on the biological foundations of human stress perceptions and reactions
- To identify possible avenues for future research on the basis of a careful review of existing empirical studies.

The information in this paper will provide both current technostress researchers and those future researchers with potential interest in the field— particularly in the IS discipline—with a comprehensive and fundamental knowledge about the foundations of biological stress mechanisms, as well as the "state of the art" in technostress research, with a focus on the biological level of analysis. By integrating an extensive number of studies from varied disciplines, the present paper develops a "big picture" of the topic of technostress and biology.

Even though this study is focused on biology, relating this stream of literature to studies at the behavioral analysis level is of essential value. Because all human behavior is determined—at least partly—by biological factors (Cacioppo et al., 2000), neither the biological nor the behavioral level of analysis would be complete without the other. This complementarity is best reflected in the structure of general stress research, which integrates biological, cognitive, and behavioral theories and data (e.g., Cooper, 2000; Cooper et al., 2001; Joels & Baram, 2009; Lazarus & Folkman, 1984; Perrewe, 1987; Perrewe & Ganster, 1989; Perrewe & Zellars, 1999).

As noted, scholars in the IS discipline are the main target audience of this article. However, it is hoped that the study can also provide value to academics in other disciplines, such as psychology, ergonomics, management, library science, human-computer interaction, and medicine. This can help to avoid "reinventing the wheel," which occurs when one discipline is not aware of empirical and theoretical findings already reported in the publication venues of outlets pertaining to other fields.

Unfolding of the Review

The roadmap of this paper is illustrated in Figure 1, in the form of a causal model.

Figure 1 (left side) indicates that, as a consequence of the perception of both *acute* and *chronic* stressors, human interaction with ICT may result in the activation of biological stress systems that span a number of physiological systems, including the central nervous system, autonomic nervous system, endocrine system, immune system, and the genetic system. Computer system breakdown is an example of an acute stressor, and elevated learning requirements due to rapid ICT developments constitute a chronic stressor (Riedl et al., 2012; Tarafdar et al., 2010).

Moreover, antecedent variables such as computer self-efficacy may affect the emergence of stressors (Jex et al., 2001; Shu et al., 2011). The activation of stress systems usually has a negative effect on well-being and health, particularly over the longer term. Importantly, the impact of ICT stressors on the activation of the biological stress systems is moderated by a number of factors, including such contextual factors as time pressure for task completion, such demographic factors as gender, such personality factors as neuroticism, and such stressor characteristics as uncontrollability. Finally, as is illustrated in Figure 1 (right side), both well-being and health may have an influence on work performance and productivity (e.g., Turner & Karasek, 1984; Wastell & Newman, 1996a), a fact that is of particular importance when technostress is studied in an organizational context.

The elements within the dotted rectangle in Figure 1 are the major focus in the present study.

The literature review focuses on the influence that different ICT stressors have on the activation of biological stress systems, including the impact of moderators (e.g., demographic variables), as well as subsequent well-being and health implications, and the performance and productivity considerations (see the causal relationships illustrated in Figure 1, center).

The discussion in the research agenda will have a wider focus—including not only theoretical, methodological, and health considerations, but also coping strategies, which may advantageously influence the activation of biological stress systems (e.g., by reducing the excretion of stress hormones). Also, the research agenda addresses design science and systems engineering, because the idea of artifacts based on bio-signals for the purpose of "stress-free" human-computer interaction has recently been presented (see Figure 1, bottom).

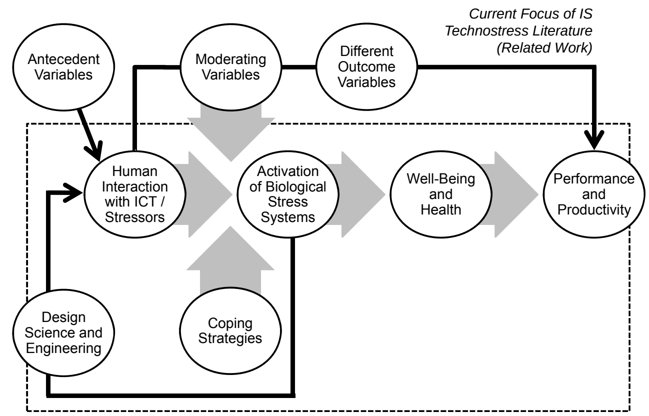

Figure 1. Roadmap of this Article

The upper part of Figure 1 illustrates the existing focus of the technostress literature in the IS discipline. To date, this focus has been mainly on the identification of both acute and chronic stressors that emerge as a consequence of human interaction with ICT. Moreover, research has studied technostress antecedents (e.g., computer self-efficacy), as well as the impact of technostress on outcome variables, particularly performance and productivity, which are major dependent variables at the end of the causal chain in IS research (e.g., DeLone & McLean, 1992, 2003). Finally, a number of moderator variables that alter the impact of technostress on outcome variables have also been identified (e.g., age).

The present focus of IS technostress literature is illustrated above the dotted rectangle in Figure 1. Despite the fact that these studies have made significant contributions to the literature, they do not adequately explain *why* and *how* stressors resulting from human interaction with technology negatively affect performance and productivity. Obviously, these effects are mediated by the well-being and health effects of biological stress systems. These themes—the why and how of technostress, and the mediating factors—are a major focus of this study.

Table 1. Related Research in the IS Discipline

Research Group	Major Findings
Group A: - Shu, Q. - Tu, Q. - Wang, K. *Data Source:* Survey (China) *Published in:* - CACM - CHB - IJHCI	This group found that specific technostress (TS) components (e.g., techno-overload), but not overall TS, negatively affect productivity. Also, they determined that individuals older than 35 years perceive a higher level of overall TS than do younger persons, and individuals performing simple tasks perceive a lower level of overall TS than do persons performing more complex tasks. Moreover, their research indicates that different organizational settings (e.g., degrees of centralization and innovation) affect employees' TS levels. Finally, results show that TS (a) is negatively related to computer self-efficacy, and (b) is positively related to technology dependence.
Group B: - Ragu-Nathan, B.S. - Ragu-Nathan, R.N. - Tarafdar, M. - Tu, Q. *Data Source:* Survey (North America) *Published in:* - CACM - ISR - JMIS	This group developed and validated instruments for measuring TS creators, namely techno-overload ("too much"), techno-invasion ("always connected"), techno-complexity ("difficult"), techno-insecurity ("uncomfortable"), and techno-uncertainty ("too often and unfamiliar"), and TS inhibitors (literacy facilitation, technical support provision, and involvement facilitation). Also, their study indicates that TS creators decrease user productivity and job satisfaction, leading to decreased organizational and continuance commitment, while TS inhibitors exert a positive influence on these outcome variables. Also, results indicate that males experience more TS than females, and TS decreases as age, education, and computer confidence increase. Finally, this group reports that overall TS positively correlates with role stress, while it correlates negatively with end user satisfaction, end user performance, and productivity.
Group C: - Ayyagari, R. - Grover, V. - Purvis, R. *Data Source:* Survey (North America) *Published in:* - MISQ	This group investigated whether technology characteristics were related to specific stressors, namely work overload, role ambiguity, job insecurity, work–home conflict, and invasion of privacy. The technology characteristics were grouped into three classes: usability features (e.g., reliability), dynamic features (e.g., speed of technological change), and intrusive features (e.g., ability to reach a person through technology). The results show that technology characteristics affect stressors, which, in turn, predict perceived strain. Also, they determined that as technology use increases, perceived stressors could also increase. Finally, the research indicates that perceived strain is affected by a person's level of negative affectivity (i.e., a general tendency to evaluate situations more negatively).

Notes: This table includes studies that were either published in IS outlets or by scholars who may be assigned to the IS discipline. To date, three major research groups have contributed to the IS literature (excluding work by Riedl et al., 2012). CACM: *Communications of the ACM*, CHB: *Computers in Human Behavior*, IJHCI: *International Journal of Human-Computer Interaction*, ISR: *Information Systems Research*, JMIS: *Journal of Management Information Systems*, MISQ: *Management Information Systems Quarterly*. TS: Technostress.

Related Work in the IS Discipline

This section summarizes technostress research published in IS outlets and by IS scholars, with a focus on peer-reviewed journal articles. With the exception of one article (which will be discussed in the literature review section), all IS papers to date have addressed technostress from a non-biological perspective—yet even without that important component, the theoretical and/or empirical contributions of the studies constitute a valuable complement to the biological streams of technostress research.

Ragu-Nathan et al. (2008), for example, investigated the influence of technostress on job satisfaction, commitment to the organization, and intention to stay. Because there were no prior instruments for measuring technostress, they first developed measurement instruments to capture technostress creators (e.g., threat to job security due to new technologies) and inhibitors (e.g., technical support provision), which were then empirically validated. This validation draws upon survey data from 608 ICT users working in multiple organizations. Their findings indicate that technostress inhibitors increase job satisfaction, as well as organizational and continuance commitment. Moreover, they found that demographic variables could significantly affect technostress perceptions—that, for example, female users experience less technostress than males, and that younger users perceive more technostress than older ones.

In another paper, Tarafdar et al. (2007) examined the influence of technostress on role stress and individual productivity.[2] They hypothesized that (a) technostress would be negatively related to individual productivity, (b) role stress would be negatively related to individual productivity, and (c) technostress would be positively related to role stress. Based on survey data from ICT users in 233 organizations, support for the three hypotheses was found.

In further studies building on their original research project, Tarafdar et al. (2010) extend their findings through a discussion of the negative influence of technostress on user satisfaction and performance (i.e., productivity and innovation in computer-mediated tasks). Moreover, the authors indicate that technostress is diminished and ICT satisfaction is increased when mechanisms facilitating involvement of users encourage them to take risks, learn, explore new ideas, and experiment in the context of ICT use. Finally, among the findings of the most recent paper from this broader research project, Tarafdar et al. (2011) report on the impact of moderator variables on technostress perceptions. Specifically, they found that men experience more technostress than women, older users experience less technostress than younger ones, and professionals with more formal education, greater computer confidence, and a longer history of computer use, experience less technostress.

A research project based on survey data from Chinese populations found that, unlike the findings of studies in North America, technostress seems to have no significant effect on employee productivity (Tu et al., 2005); furthermore, employees from companies with a high degree of both centralization and innovation perceived higher levels of technostress than employees in organizations with a low degree of centralization and innovation (Wang et al., 2008). Moreover, the same authors investigated the impact of computer self-efficacy (defined as a person's belief in his or her own capability to use a computer) and of technology dependence (defined as the extent to which individuals depend on computer-based technology to finish their jobs) on technostress (Shu et al., 2011). Based on survey data from 289 users in 22 organizations, the results indicate that individuals with a higher level of computer self-efficacy have lower levels of technostress than do individuals with lower levels of computer self-efficacy, while individuals with higher levels of technology dependence have higher levels of technostress than do individuals with lower levels of technology dependence.

Finally, with respect to the antecedents of technostress, one investigation (Ayyagari et al., 2011) hypothesizes that technology characteristics could be related to specific manifestations of stress (e.g., work overload). These characteristics were grouped into three categories—usability features such as system reliability, dynamic features such as speed of technological change, and intrusive features such as ability to reach an individual through technology (e.g., e-mail). Drawing upon survey data from 661 working professionals, the hypothesis was supported.

The central results from IS technostress literature review are summarized in Table 1. One observation is that research on technostress, so far, has been conducted by a very limited number of IS scholars, if peer-reviewed articles in mainstream journals are used as a benchmark. This limited number of scholars is organized in three major research groups, whereas one individual belongs to two groups. The summary in Table 1 is structured along these three groups and the names within the groups are listed in alphabetical order (year of the first publication of a group is used to assign the letters A, B, and C).

Biological Foundations of Stress

Threats to security and well-being are a pervasive influence on human existence. The evolutionary consequence has been the development of a natural instinct for humans to strive to sustain homeostasis, a state of the biological system in which the body is in a stable and constant condition (Cannon, 1932). Without such a stress-response mechanism, it would be difficult to survive (Selye, 1946).

Humans, in a general sense, must cope with a nearly unlimited number of stressors, both physical (e.g., noise, lack of sleep, or low blood sugar) and psychological (e.g., public speaking, social rejection, or, as a more recently generated stressor, human-computer interaction). Despite this basic distinction, however, both types of stressors have been shown to

[2] Role stress is defined by (a) lack of clarity regarding the scope of personal responsibilities, (b) a condition of having more assigned roles than can reasonably be handled, and (c) contradictory requirements arising from different aspects of the role.

substantially activate biological stress systems in humans (e.g., Lazarus & Folkman, 1984).

Saliently, for this study technostress is conceptualized as a psychological stressor. Therefore, any possible stress reactions of ICT users that are a consequence of various forms of electric and magnetic fields are beyond the scope of this article.[3]

A discussion of the general biological foundations of stress may refer to four levels of analysis (Cacioppo et al., 2007; Canli, 2009; Dickerson & Kemeny, 2004; Joels & Baram, 2009):

- Genetic system
- Central nervous system
- Autonomic and somatic nervous systems
- Endocrinological system.

In the discussion that follows, important biological foundations of stress are based on these four levels of analysis; for more comprehensive reviews, see, for example, Gunnar and Quevedo (2007), as well as Joels and Baram (2009). Rather than providing an extensive account of the subject from a purely biological viewpoint, and based on the "language" of biologists and other natural science researchers (e.g., the variant 5-HTTLPR in the serotonin transporter gene SLC6A4; from Gunnar & Quevedo, 2007, p. 162), my objective is to outline fundamental mechanisms in language that are easily accessible to the behavioral researcher. After the discussion of the four levels of analysis, a summary and integration of the biological foundations of stress are presented.

Genetic System

The question of the ways in which nature and nurture contribute to the manifestation of human perception and behavior (e.g., fight or flight, in stressful situations) has been a fundamental research issue in psychology, as well as in other disciplines (e.g., cognitive neuroscience). In general, though there have been scholars with extremist beliefs and attitudes who have argued that either the biological influences of nature (particularly genes) or the environmental influences of nurture (e.g., socialization) are decisive, there is currently wide agreement that both are important and neither is deterministic (Johnson, 2007). Empirical evidence shows that human perception and behavior are the result of the interplay between both biological and environmental factors (e.g., Cacioppo et al., 2000).

Every human has a specific genetic predisposition that also concerns biological mechanisms that are associated with stress perceptions and reactions. Specifically, these genes influence the production and release of stress hormones, a process that is often mediated by the anatomy and functionality of the brain, because neuronal populations in specific brain areas release hormones, while others have receptors for specific hormones. The release of a stress hormone in a specific brain area, as well as an uptake of stress hormones via receptors, affects activation in that specific region. This, in turn, may lead to significant perceptual, emotional, cognitive, and behavioral consequences (e.g., Joels & Baram, 2009).

Research based on twin study designs indicates that reactivity of the hypothalamic-pituitary-adrenocortical (HPA) axis elicited by psychosocial stress is partly heritable (Federenko et al., 2004); the HPA axis is the major biological stress system in humans (details are provided in the section "Endocrinological System," see below).[4]

A crucial gene with effects on the reaction of the HPA axis is the brain-derived neurotrophic factor (BDNF) gene. This gene has a particularly critical role because it modulates activity in the hypothalamus, a brain region that is important in stress situations (details are provided in the section "Central Nervous System," see below).

In a pioneering study, Shalev et al. (2009) investigated the association between a specific variant of the BDNF

[3] An example is the effect that technologies such as mobile phones and wireless Internet networks have on humans. Further insights into this topic, including several noted references to related work, can be found in Arnetz and Wiholm (1997, pp. 37-38), Weaver (2002), Pau et al. (2005), Johansson et al. (2010), and Khalid et al. (2011). Moreover, the website of the World Health Organization (www.who.int) provides information on this issue.

[4] Twin study designs are based on the following logic: To investigate whether humans are endowed with genetic variation that could account for individual differences in a specific trait, perception, or behavior (e.g., reactivity to or perception of stress), both monozygotic (MZ) twins' and dizygotic (DZ) twins' biological stress reactions (e.g., release of hormones in a stressful situation) are measured in an experiment, and they typically also provide self-reported data on their level of perceived stress. Then, because MZ twins share the same genes (though rare exceptions are possible), whereas the genes of DZ twins are imperfectly correlated, if genetic differences help explain the variance in a specific trait, perception, or behavior, MZ twins should exhibit a higher correlation in their levels of that specific trait, perception, or behavior than DZ twins (given that possible differences in the environments in which these individuals were raised are controlled for). More details on the logic of twin studies can be found, for example, in Plomin et al. (2008).

gene (the Val66Met polymorphism) and HPA reactivity (measured via the stress hormone cortisol, as well as blood pressure and heart rate). Principally, the results indicate a gender-dependent effect of this gene variant, pointing to an attenuated HPA reactivity in male subjects. This finding was later replicated in experiments that were based on a public speaking task (Alexander et al., 2010), and on a cold pressure test (Colzato et al., 2011). Importantly, the replication study by Alexander et al. reveals that for male carriers of this specific gene variant (the met-allele), the diminished biological response is associated with significantly lower self-reported ratings of perceived stress and nervousness.

Reflecting on their results, Alexander et al. (2010, p. 952) write that "diminished physiological stress reactivity in met-allele carriers might simply reflect stable differences in the perception of stressful situations, since the attenuated endocrine and cardiovascular stress response observed in these subjects was also attended by lower ratings of perceived stress and nervousness." Thus, carriers of this specific gene variant (the met-allele) show lower values in personality traits related to anxiety, such as neuroticism (Frustaci et al., 2008), and are likely to respond less intensely in stressful situations.

With respect to *neuroticism*, research has revealed further insights with significant implications for genetic stress research. Specifically, Canli (2009) discusses neuroticism, as well as its relation to stress, from a genetic viewpoint.

Neuroticism is defined as heightened negative affect, and it influences stress perceptions and health. Twin studies by Canli (2009) indicate that 40–60% of neurotic behavior (as well as corresponding stress perceptions and, possibly, health consequences) can be attributed to genetic makeup. On the basis of these findings, researchers have sought to identify further candidate genes (in addition to the BDNF gene).

In a pioneering study, Caspi et al. (2003) found that a specific variant of the serotonin transporter gene polymorphism, in combination with a history of stressful life events, may significantly increase an individual's vulnerability to depression. Because serotonin plays an important role in the reduction of post-stress anxiety (Adamec et al., 2008), it is theorized that this specific genetic makeup, shaped by specific environmental influences (e.g., low degree of social support in stressful situations), hampers the recovery process after stressful situations. [5] This, in turn, negatively affects health, particularly in the long term (e.g., Canli, 2009; Joels & Baram, 2009).

In addition to the subject of neuroticism, which is used here as an example of a personality trait with major implications for stress perceptions and reactions, research has also investigated the genetic foundations of several other potentially stress-relevant personality traits, including harm avoidance, impulsiveness, risk perception, and positive emotionality. In a review of the genetic and environmental influences on human psychological difference, Bouchard and McGue (2003) conclude that "there is strong evidence that … psychological differences, when reliably measured, are moderately to substantially heritable" (p. 4).

To sum up, current research indicates that a significant amount of both stress perceptions and reactions could be genetically predetermined. [6] Despite this fact, however, there is wide agreement among scientists that such genetic predispositions, in general—and, thus, also those pertaining to stress—are shaped by interaction with the environment, a phenomenon referred to as epigenetics. Therefore, it is possible that a person who is actually stress-predisposed, and who has repeatedly experienced stress-reducing factors, may be more relaxed than stressed in his or her life. An example for a stress-reducing factor would be a learned schema from childhood that other humans are benevolent rather than malevolent that increases a general feeling of social support.

The following systems to be described—the central nervous system, and the autonomic and somatic systems, are characterized by functioning that is significantly shaped by genetic factors.

Central Nervous System

The central nervous system consists of the brain and the spinal cord. While the brain is mainly responsible for information processing and integration, the spinal cord transmits information from the brain to various parts of the body (e.g., musculoskeletal system), and vice versa. For example, when a person perceives a visual stimulus, the eyes send information to the brain, which then appraises the situation (note that this often occurs as an unconscious action). In the case of a stimulus that is life-threating (implying high levels of stress), the brain, along with other reactions such as the release of hormones, sends signals via the spinal cord to the musculoskeletal system (as an example, a signal that triggers a flight response).

[5] Note that serotonin also has other stress-related functions, which are described, for example, in Skuse and Gallagher (2011).

[6] Further candidate genes related to HPA axis reactivity are discussed in Derijk (2009).

Several areas in the human brain release specific stress hormones, and other regions have specialized receptors that make an uptake of these hormones possible (e.g., Joels & Baram, 2009). Importantly, both release and uptake of a stress hormone activate a specific brain area, thereby triggering activation in further brain regions, setting in motion a chain of other biological, perceptual, emotional, cognitive, and ultimately, behavioral processes (e.g., Kolb & Whishaw, 2009).

One recent review (Gunnar & Quevedo, 2007) identified the following brain regions as important for the neural implementation of stress: amygdala, anterior cingulate cortex, brain steam nuclei and medulla, hippocampus, hypothalamus, orbital frontal cortex, and pituitary gland. Most of these brain regions are phylogenetically old—that is, evolution has shaped their development during several epochs since the emergence several million years ago of the human species and its ancestors (Kolb & Whishaw, 2009).

Identifying the brain areas related to stress is important, because too much or too little activation in these regions may have significant implications for stress perceptions and reactions. For example, high activation in the amygdala is reported to be correlated with self-reported stress (for a review, see Canli, 2009).

Theoretically, this result can be interpreted in two ways. First, it is possible that once an individual is exposed to a potentially stressful situation, this brain region, the amygdala, becomes pathologically activated, thereby significantly increasing stress perceptions which, in turn, may result in higher levels of general anxiety and alterations in behavioral performance. Second, it might also be possible that high amygdala activation is more a "trait-like chronic" response (Canli, 2009, p. 301).

This distinction, importantly, is not only of theoretical significance, but is also practically relevant. In the former case, the pathology is an overreaction of the amygdala in stressful situations. In the latter case, an individual will be permanently stressed (due to chronic activation in the amygdala), even though stressors are possibly not effective at all. Obviously, this differentiation may influence a number of outcome variables, such as well-being and health, or performance and productivity.

Autonomic and Somatic Nervous Systems

The autonomic nervous system consists of two divisions: sympathetic and parasympathetic. While the main function of the former is the implementation of a "fight-or-flight" response (hence being stimulatory), the latter implements a "rest and digest" response (hence being inhibitory) (Kolb & Whishaw, 2009).

In contrast, the somatic nervous system consists of cranial and spinal nerves to and from the sensory organs, muscles, joints, and skin. The main functions of the somatic nervous system are the production of movements and the transmission of sensory information (e.g., vision, temperature, touch). Even though the somatic nervous system might have significant relevance in specific stress situations (e.g., execution of movements to flee), the following discussion is focused on the autonomic nervous system, because technostress is, for this study, framed as a psychological stressor, for which movements are not directly in the center of interest.

Consider a situation in which an individual is confronted with an acute stressor such as the Trier Social Stress Test (TSST; Kirschbaum et al., 1993), which is a procedure that allows researchers to induce stress under laboratory conditions. The TSST includes, for example, public speaking and mental operation tasks in front of an interview panel.

In most humans, such a situation will trigger a response of the sympathetic division of the autonomic nervous system (e.g., Kolb & Whishaw, 2009). Among other responses, this includes the following biological reactions: (a) pupil dilation (i.e., increase of attention), (b) skin conductance elevation, (c) airway relaxation, (d) heartbeat acceleration, (e) intense glucose release, and (f) muscle tension. The primary function of these reactions is to prepare the body for the stressful situation in order to secure optimal performance. Moreover, bodily processes that are not crucial in stress situations are suppressed (e.g., salivation and digestion).

However, despite the fact that the described stress response is essential in order for humans to perform well, or even to survive, it is equally important to shut down these processes at some point in order to recover from a stressful event and its underlying biological processes. Selye (1946), in particular, has indicated in his seminal work on the General Adaptation Syndrome (GAS) that prolonged activation of the sympathetic system will lead to a "stage of exhaustion," where irreversible physical damage appears (e.g., loss of neurons in memory-related brain areas such as the hippocampus) and, if the stressor persists, the organism dies.

To avoid this "stage of exhaustion," the parasympathetic division of the autonomic nervous system becomes activated (e.g., Kolb and Whishaw, 2009). Unlike the sympathetic system, its activation leads to reverse effects: (a) pupil contraction (i.e., decrease of attention), (b) skin conductance reduction, (c) airway constriction, (d) heartbeat slowdown, (e) no glucose release, and (f) muscle relaxation.

In this context, Yerkes and Dodson (1908) proposed a universal law stating that the relationship between stress/arousal (x-axis) and performance (y-axis) approximates an inverted U-shaped curve. Accordingly, increments of stress improve task performance up to a certain point, beyond which more stress leads to decreases in performance. The biological foundations of this law are related to activation of the autonomic nervous system. As a rule of thumb, an individual benefits from activation of the sympathetic system up the maximum of the curve, while he or she benefits from activation of the parasympathetic system beginning at the maximum.

The next system to be discussed is the endocrinological (hormonal) one, which is related to the central, autonomic, and somatic nervous systems.

Endocrinological System

Endocrinology is a scientific field dealing with the hormone system. Among topics such as the chemistry of hormones that are less relevant for the behavioral sciences, this field investigates the physiological functions of hormones. In general, hormones are chemicals released by glands or cells that act as messengers in the body. That is, they convey messages from one part of the body to another. This function, obviously, makes hormones crucial substances in stress situations, because success of the complex interplay among various body parts may determine, in the most extreme case, survival.

The literature describes a wide range of hormones that play an important role in stress situations (for a recent review, see Joels & Baram, 2009). Despite the complexity of the interchanges, however, there are a few "key players" that are the focus of the following discussion. Though the narrow focus is useful for this analysis, it is important to note that many stress hormones are interrelated (both those discussed here and others less prominent), typically acting in concert rather than in an isolated fashion.

In a stress situation, two major biological systems become activated: sympathetic-adrenomedullary and hypothalamic-pituitary-adrenocortical (HPA). The former system controls the stress response and describes the "[o]utflow of sympathetic autonomic nervous system that triggers rapid physiological and behavioral reactions to imminent danger or stressors," while the latter system "describes the complex chain of physiological events that characterizes … stress response systems" (Gunnar & Quevedo, 2007, pp. 147-148).

The sympathetic-adrenomedullary system functions as follows: In a stress situation, the sympathetic division of the autonomic nervous system, based on activation in the hypothalamus, stimulates the adrenal glands, and, as a consequence, the adrenal medulla, a specific part of the adrenal glands that releases the hormones adrenaline (also known as epinephrine) and noradrenaline (also known as norepinephrine). Once released, these two hormones bind to receptors of target organs, triggering a number of biological reactions that play a role in the preparation of a "fight-or-flight" response (e.g., increasing heart rate and securing availability of glucose). Adrenaline and noradrenaline belong to a group of chemicals referred to as catecholamines.[7]

As a correlative, the basic functioning of the HPA system can be described as follows (e.g., Tsigos & Chrousos, 2002): In a stress situation, specific brain areas become activated. Among these are regions that integrate sensory information from the environment (e.g., thalamus and frontal cortex) and, in particular, limbic regions that are related to the processing of emotions.

The hypothalamus is a fundamental structure of the limbic system, as well as a control center for the hormone system. This structure has the critical function of releasing corticotropin-releasing hormone (CRH) in stress situations, which influences activation in the pituitary gland. This activation, in turn, induces a release of adrenocorticotropic hormone (ACTH), a substance that travels in the blood to the adrenal glands, where it stimulates the release of cortisol into the bloodstream.[8]

Cortisol mediates a number of biological, cognitive, and behavioral stress responses (e.g., Dickerson & Kemeny, 2004; Foley & Kirschbaum, 2010). For example, it enhances blood sugar and delays bodily processes that are irrelevant in a stress situation (e.g., digestion). Moreover, it has been shown that exogenously administered cortisol may ameliorate emotional states (Reuter, 2002). One of the major effects, however, is that acute cortisol responses, unlike chronic ones (e.g., Kim & Diamond, 2002), may enhance memory (for a review, see Het et al., 2005).

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[7] The well-known hormone dopamine, for example, which is mainly involved in reward perception and processing but also has a role in stress reactions, also belongs to this group (e.g., Schultz, 2006).

[8] In addition to the well-known stress hormones (adrenaline, noradrenaline, and cortisol), the enzyme *alpha-amylase* is another important indicator of stress. Because this enzyme can be measured through salivary analysis, measurement of alpha-amylase is non-invasive, uncomplicated, and relatively quick. Insights related to stress measurement based on alpha-amylase can be found, for example, in Noto et al. (2005), Granger et al. (2007), and Harmon et al. (2008). As well, a pioneering study by Tams (2011) uses this measure with a specific emphasis on assessing stress in an IS context.

If compared to the function of adrenaline, which primarily generates a state of arousal, cortisol also serves the function counteracting this primary stress response, thereby contributing to the reestablishment of homeostasis. This function of cortisol supports negative feedback inhibition, thus reducing activation in structures that release CRH (hypothalamus) and ACTH (pituitary gland).

Summary

Figure 2 conceptually summarizes the discussion on the biology of stress by illustrating biological systems pertaining to the four levels of analysis: genetic, central nervous, autonomic and somatic nervous, and endocrinological. A brief discussion addressing the integration of the four levels of analysis allows for explanation of the *causal chain of biological processes* that take place in stress situations.

Stressors, such as those associated with human-computer interaction, have an influence on the activation of biological systems, and the potential for activation is affected by genetic predisposition (e.g., specific gene networks have an effect on personality traits such as neurotocism that affect stress perceptions and reactions). Once an individual perceives a stimulus (e.g., via the somatic nervous system), specific brain regions such as the thalamus and frontal cortex integrate corresponding information based on sensory perception (e.g., a visual stimulus). Then the brain appraises the meaning of this stimulus (a context-dependent process which is often associated with memory processes), and this appraisal, which is usually an unconscious activity that may take place in less than a second, leads to the generation of emotional responses that are mediated by the limbic system and by other brain regions (e.g., brain steam and pituitary).

Major areas of the limbic system that have implications for stress perceptions and reactions are the amygdala, hippocampus, anterior cingulate cortex, and hypothalamus. In particular, the hypothalamus plays a significant role in stress situations because it acts as a control center for the neuroendocrine system (see Figure 2).

On the one hand, the hypothalamus activates the sympathetic division of the autonomic nervous system (sympathetic-adrenomedullary system), thereby stimulating activity in the adrenal medulla. This, in turn, leads to a release of both adrenaline and noradrenaline, and these two substances prepare the body for a "fight-or-flight" response (see the six reactions illustrated in Figure 2, such as heartbeat acceleration).

On the other hand, the hypothalamus, via the parasympathetic division of the autonomic nervous system (HPA system), releases corticotropin-releasing hormone (CRH), which, in turn, influences activity in the pituitary gland, thereby triggering the release of adrenocorticotropic hormone (ACTH). This substance then travels in the blood to the adrenal glands, where it stimulates the release of cortisol into the bloodstream (Figure 2), implementing a "rest and digest" response, with the goal of shutting down the stress reaction.[9]

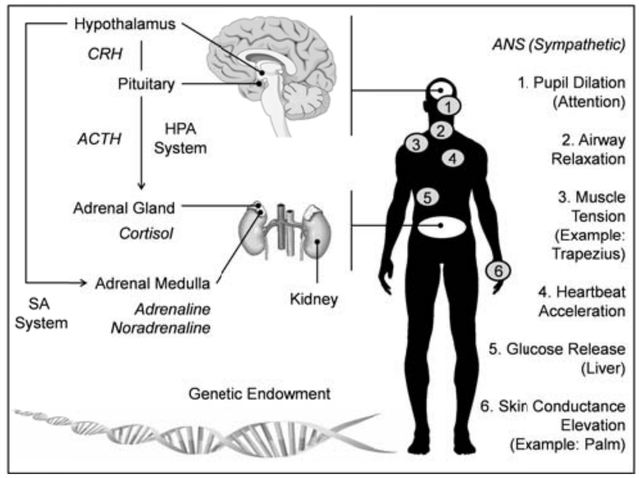

Figure 2. Human Stress System

Notes: ACTH: Adrenocorticotropic hormone; ANS: Autonomic Nervous System; CRH: Corticotropin-releasing hormone; HPA system: hypothalamic-pituitary-adrenocortical; SA system: sympathetic-adrenomedullary. The adrenal medulla is part of the adrenal gland. The trapezius is on the back between the head and the shoulder, but for simplicity is illustrated from front side. Muscle tension and skin conductance elevation locations are examples of measurement points. Brain: Lateral View. Healthy humans have two kidneys and two adrenal glands.

Investigations into stress imply knowledge about the activation timeline of the biological systems illustrated in Figure 2. Beginning with stimulus perception, the preparation of the "fight-or-flight" response only takes a few seconds (Birbaumer & Schmidt, 2010, p. 150). Consequently, autonomic nervous system activity can be measured almost instantaneously. Skin

[9] It is important to note that the four biological levels of analysis are closely interrelated (e.g., Cacioppo et al., 2000). Major interrelationships are: (a) genes influence the anatomy and functionality of the brain (central nervous system), as well as the release of hormones; (b) hormones influence activity in areas of the brain because specific regions have receptors for certain hormones; (c) the brain influences hormones because it regulates both their production and release; and (d) the central nervous system affects the autonomous nervous system because the hypothalamus is the starting point of activity in both the sympathetic and parasympathetic systems.

conductance (see number 6 in Figure 2), for example, has a one- to three-second latency from stimulus perception to onset of the response, and the peak amplitude is typically reached within another one to three seconds after the onset of the response (e.g., Dawson et al., 2011). Other reactions of the autonomic nervous system such as pupil dilation, as well as the preceding cortical processes, can be even faster (typically measured in milliseconds). However, depending on the specific indicator at hand, temporal resolution can vary from milliseconds (e.g., pupil dilation or EEG signal) to several seconds (e.g., the blood-oxygen-level-dependent (BOLD) signal that is used in fMRI studies).[10]

In contrast to the very fast activation of the sympathetic-adrenomedullary system, activation of the HPA system takes a few minutes (Birbaumer & Schmidt, 2010, p. 150). Moreover, it often takes half an hour or even longer after the onset of the response until the peak amplitude is reached. Specifically, cortisol levels have been shown to peak 10–40 minutes after stressor onset, depending on stressor type, and because ACTH is a precursor substance of cortisol, it peaks earlier, usually 10–20 minutes after stressor onset (Dickerson & Kemeny, 2004).

Literature Review

In this section, a review of the technostress literature based on biological measures is provided. The studies were identified through the procedure described in the Appendix.[11] Drawing upon the previous section, the review is structured along the four levels of analysis relevant in human stress research. Because technostress research pertaining to the genetic and central nervous system levels has received no significant attention in the literature, the following discussion is mainly focused on investigations into the effects of technostress on the autonomic nervous system and endocrinological system. Within these two categories, the scientific literature is grouped into two classes:

- *Field studies* (including investigations into the negative biological effects of the implementation of information systems in organizations, as well as studies, in the context of technology introductions in organizational settings, that investigated the positive biological effects of interventions such as stress management techniques)
- *Laboratory experiments* (including studies on the negative biological consequences of acute stressors such as response times or computer system breakdowns).

Genetic System

Based on the procedure described in the Appendix, no relevant technostress studies could be identified in this category.

Central Nervous System

One technostress study was identified in this category. Trimmel and Huber (1998) studied stress-related after-effects of human interaction with computers by means of EEG. A total of 49 individuals were recruited to participate in a laboratory experiment (mean age: 24 years; range: 17–42; 21 females and 28 males). The subjects were grouped into (a) naive non-computer users (*N*=15, persons who never previously used a computer), (b) beginners (*N*=13), (c) experienced users (*N*=11), and (d) programmers (*N*=10). The participants completed three paper/pencil tasks (text editing, solving intelligence test items, and filling out a questionnaire), as well as three human-computer interaction tasks (text editing, executing a tutorial program or programming, and playing the video game Tetris). Each task lasted seven minutes, and the order was randomized. After each experimental condition, event-related brain potentials (ERPs, a specific type of EEG data) were recorded (points on the scalp: F3, F4, Cz, P3, and P4). The results of this study show notable effects, two of them are presented here due to their relevance for technostress.

First, the P300 amplitude was smaller after the human-computer interaction tasks, if compared to the paper/pencil conditions. Importantly, reduced P300 amplitudes ”can be interpreted as a sign of fatigue or depletion of resources” (p. 654). Thus, a major

[10] The electroencephalogram (EEG) measures voltage fluctuations on the scalp that result from changes in membrane conductivity elicited by synaptic activity and intrinsic membrane processes. Electrodes on the scalp capture the summed postsynaptic potentials generated by a large number of neurons. Functional magnetic resonance imaging (fMRI) tracks blood oxygenation in the brain and exploits the different magnetic properties of oxygenated and deoxygenated blood (the so-called BOLD contrast). Simultaneous direct recording of neural processing and fMRI responses shows that the BOLD signal reflects the parameters of neural activity reasonably well (definitions taken from Riedl et al. 2010a, p. 246).

[11] It is important to mention here that in order to guarantee the academic quality of studies included in this review, an essential selection criterion was that the paper must have been published in a peer-reviewed scientific journal or conference proceedings.

conclusion of this brain imaging study is that human interaction with computers may lead to stress-like consequences such as fatigue.[12]

Second, the study reports that this neuronal after-effect is independent of the users' computer experience (so that there was very little difference between the four groups). The authors note, however, that it is important to consider that immediate after-effects of human-computer interaction were measured, and therefore no conclusions can be drawn about "structural changes in cortical information processing" (p. 654). Thus, it remains unclear whether human-interaction with computers causes biological stress that has a direct influence on detrimental changes in the brain, such as loss of neurons. Considering that stress research in other domains has already determined that stress may lead to structural changes in brain regions that are important for the neural implemenation of memory (e.g., hippocampus; Kim & Diamond, 2002), there is no reason to assume that stress perceptions originating from human interaction with ICT are immune against such fatal biological effects.

Autonomic and Somatic Nervous Systems

Seven technostress studies were identified in this category; three of them are field studies, while the remaining four are laboratory experiments.

Field Studies

A two-stage field study (Johansson and Aronsson 1984) conducted in a Swedish insurance company assessed, in the first stage, psychosocial stressors and symptoms related to work at computers in a client-server architecture, where stressors (e.g., rush, effort) and symptoms (e.g., irritation, fatigue) were measured by means of a multi-item survey instrument. (Note that in the 1980s and 1990s computers were often referred to as video display units, VDUs.) In the second stage of the study, 11 users with extensive computer work (i.e., more than 50% of working time is computer-based; mean age: 43 years; age range: 25–59) and 10 individuals with a low degree of computer work (i.e., not more than 10%; mean age: 46 years; age range: 37–52) were investigated in detail. All 21 persons were female.

Specifically, these two groups were studied during (a) regular work and (b) leisure time (i.e., at home), as well as (c) during the unplanned breakdown of the enterprise system. In this second stage, self-reported data on both mood and alertness were collected, as was biological data on blood pressure, heart rate, and excretion of adrenaline and noradrenaline (based on urine samples; note that the hormone results of this study are discussed in the next section).

The results show that stress (blood pressure, heart rate), as well as psychosocial stressors and symptoms (survey measures), were comparatively higher in the group of individuals with extensive computer work (both at work and home).

Other important findings of this study are that (a) the nature of the task (monotonous data-entry versus decision support) and (b) the amount of computer work both predicted mental strain (survey measurement). Individuals performing monotonous computer work also displayed a higher level of physiological arousal during post-work hours than did control subjects. In other words, there is a tendency to "take" stress from work to home.

Interestingly, an unplanned (and hence real) breakdown of the computer system took place in the firm during the investigation, and an "improvised mini-study" (p. 175) was conducted. The results of this study are based on a sample of six individuals. Despite this small sample size, however, computer breakdown led to a significant increase in diastolic blood pressure, if compared to baseline values from the regular operation phase. Note that systolic blood pressure and heart rate also increased; however, these two elevations were statistically not significant.[13]

However, despite the fact that this study found notable degrees of technostress (based both on self-report instruments and biological measures), the authors are optimistic that specific countermeasures may mitigate the problem. They concluded that "stress and strain in computerized work may be counteracted at the technological and the organizational level: by reducing the duration and frequency of breakdowns, by reducing response times in the system, and by eliminating pure data-entry tasks" (p. 159).

Based on three biological measures, namely electromyogram (EMG, to determine physical strain), heart rate variability (HRV, to determine mental strain), and electrodermal activity (EDA, to determine

[12] Developing a study based on a simple data-entry task, Floru et al. (1985) did not find effects of human interaction with computers on EEG patterns.

[13] Blood pressure (BP) is the pressure exerted by circulating blood upon the walls of blood vessels. During each heartbeat, BP varies between a minimum (diastolic) and maximum (systolic). An individual's BP is typically expressed in terms of the systolic over diastolic pressure, and is measured in millimeters of mercury (mmHg). A value of 120/80, for example, is typical for a healthy adult.

emotional strain), another field study (Boucsein & Thum, 1997) investigated the design of work and rest schedules for computer workers who have to carry out a demanding decision-making task.[14] Specifically, they studied 11 patent examiners in a European patent office in the Netherlands who were using a new information system for the examination of patent applications (10 male, 1 female; mean age: 32.6 years; SD: 5.2). The examiners had electronic access to patents, and their task was to write a report about the novelty of an application, with writing the typical report taking up to two days to complete. A university degree is a required qualification to qualify for this job. Obviously, these characteristics distinguish this kind of computer work from standardized computer-based tasks such as pure data entry.

In the field study, the patent examiners performed their complex work at the computer under two different break designs (the order was counterbalanced): (a) a break of seven and a half minutes after 50 minutes of work (short break) on one day, and (b) a break of fifteen minutes after 100 minutes work (long break) on another day.

The results of the study indicate that short breaks were more effective in facilitating recovery from both mental (HRV) and emotional (EDA) strain—that is, until the early afternoon. In contrast, the long break was more effective in lowering emotional strain (fatigue) in the late afternoon. Moreover, it was found that recovery from physical strain (EMG) was greater during scheduled breaks, as compared to unpredictable breaks. (The study investigated system breakdowns and interruptions by colleagues.) However, because emotional strain was also higher during scheduled breaks, if compared to breakdowns and interruptions by colleagues, the authors indicate that it is ”not appropriate” to have ”a rigid break schedule” (p. 57) for highly complex computer-based decision-making tasks (as it might be desirable for more monotonous works such as data entry), because a break is only desirable once a specific homogenous cognitive task has been completed, rather than stopping due to an ex-ante specified break. Finally, the study also demonstrates that neck EMG (a specific form of muscle tension) increases markedly during system breakdowns, which indicates ”an *increased total strain* during these types of unexpected interruptions” (p. 56, italics in original).[15]

A research project from Great Britain also makes a significant contribution to the creation of a better understanding about the potential stress related to information system implementation (see publications on this project: Wastell & Newman, 1993, 1996a, 1996b and Wastell & Cooper, 1996).

This research was designed as a comparative case study that includes two organizations, both ambulance services—one in London and the other in Manchester. For both organizations, the object of the study was the implementation of a new computer system for control-room operations. This context was selected deliberately for the study because the environment is, by nature, already very demanding, as ”lives depend upon the efficient and expeditious decisions of the human operators [and] any changes that exacerbate the already stressful nature of the job would be catastrophic” (Wastell & Newman, 1996a, p. 184).[16]

The investigation was conducted based on the assumption that the implemenation of new technology is a ”highly problematic process,” because it is related to factors such as increased routinization, raised stress levels, and reduced job satisfaction (Wastell & Cooper, 1996). Also, Wastell and colleagues hypothesize that a ”user-centered” introduction of the system positively affects satisfaction and resulting work performance, and that this relationship is influenced by well-being, a factor that was measured through two biological indices (heart rate and blood pressure), as well as through two subjective survey measures (anxiety and fatigue).

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[14] Note that the selection of heart rate variability (HRV) as a physiological measure for “mental strain/stress” is in line with reports in the literature that indicate that “HR-derived variables reflect the central pathway in cardiovascular control mechanisms and are thus a sensitive measure of mental stress” (Hjortskov et al., 2004, p. 88). For further details on HRV see, for example, Camm et al. (1996).

[15] Note that muscle tension (e.g., tension of the trapezius) as a result of incorrect body posture during interaction with a computer is not discussed in this article. There exists, however, an overwhelming body of literature on this topic; see, for example, recent work by Mork and Westgaard (2007), as well as Schleifer et al. (2008), and the cited references in these two papers. Similarly, the effects of human-computer interaction on “visual fatigue” (Murata et al., 1991) and “visual stress” (Zhang et al., 2004) are not discussed in this article, because these topics are not directly related to technostress. Moreover, it is important to note that brief rest pauses (e.g., 30 seconds) during human-computer interaction, particularly during repetitive data entry tasks, positively affect well-being by reducing heart rate (Henning et al., 1989).

[16] This is a strong example showing the importance of technostress research. Based on this instance it becomes obvious that not only is the influence of stress perceptions harmful to a user’s own health, but the resulting reduced user performance, with its influence on the health of other people, is also harmful (and in this case may even impact survival).

The selection of these two biological measures is well-justified in the study, with the authors (Wastell & Newman, 1996a) specifically addressing the issue, and indicating that ”[o]f the wide range of psychophysiological parameters (such as EEG-based or electrodermal measures) that were considered as candidates for the study, the decision was made to adopt cardiovascular indices. One reason was practical, namely that it was readily feasible to record heart rate and blood pressure with minimal intrusion under operational conditions. The central role played by the cardiovascular system in the ’stress response’ provided a more fundamental reason for the choice” (p. 184).

The results of the study demonstrate that the project outcomes were different in the two organizations. In London, significant problems resulted in the abandonment of the system implementation. In Manchester, in contrast, the new system led to both reduced stress and improved service levels. In the following, the specific study design with respect to the successful implementation in Manchester is outlined.

This longitudinal study involved two phases of data collection (each lasting six weeks), namely before the implementation of the new system (baseline) and afterward (post-implemenation). In the seven months between the two data collection phases, the system was effectively put in place, and was already ”running smoothly” in the second phase (Wastell & Newman, 1996a, p. 186).

The entire sample consisted of 45 workers (e.g., call takers and dispatchers), of which 90% were female (age range: 19–55 years). Due to specific quality control criteria defined for the two biological measures, reliable data was ultimately available for 18 operators. The researchers also assessed workload (in the study, defined as simultaneous active jobs).

The results indicate that the increase of systolic blood pressure with workload was steeper for the paper-based system than for the new computer system. Moreover, the results of the post-implementation questionnaire show that both anxiety and fatigue had not increased as much in the work with the new system, if compared to the paper-based system. However, this difference was statistically insignificant. Based on these results, the authors developed the following conclusion (Wastell & Newman, 1996a): ”The psychophysiological results provide a cogent demonstration of the benefits to be gained by designing systems to support human users. The results show that, whereas rising work demands evoke an increase in cardiovascular activation and subjective anxiety for both paper-based and computerized operation, the magnitude of this ’stress response’ was significantly lower for the computer-based system. This strongly suggests that [the new system] enabled operators to cope more easily with work demands, i.e., with less psychological and physiological strain. We may attribute this to the greater feeling of control endowed by the system” (pp. 189-190).

Laboratory Experiments

A study conducted by Emurian (1991) investigated differences in biological measures between the completion of a human-computer interaction task and a baseline task (functionally, resting), but reading was permitted because "subjects will fall asleep during a 1-h interval without some activity to engage them" (p. 296). Specifically, this experiment investigated systolic and diastolic blood pressure, mean arterial blood pressure, heart rate, and masseter muscle electromyograph (EMG) response.[17]

Ten male subjects with computer experience (mean age: 23.1 years; range: 19–33; SD: 4.6) had to solve 50 database queries presented consecutively on a computer screen. To prevent a lowering of potential earnings ($10), each query required a solution within 45 seconds after its presentation, and a solution required the correct selection of 3 successive hypertext indices hierarchically structured from the query to the data answer. By design, time pressure was implemented in this experiment, and the author notes that this was done to create a “realistic computer-based task” (p. 305). Moreover, an eleventh male subject (age: 29 years) was studied in detail to gain insight into habituation effects.

Based on a within-subjects design, performance and baseline (resting) sessions were held on different days, with no more than seven days between the two sessions. Another important variation in this study was system response time. In one condition, each selection of a hypertext index was followed by an 8-second delay before another database level was presented; in another condition, response times varied between 1 and 30 seconds, with a mean of 8 seconds.

The results of the study indicate that systolic blood pressure, mean arterial blood pressure, and heart rate changed significantly over baseline, while diastolic blood pressure and masseter muscle EMG response did not. No differential biological effects of system response time conditions were found. Based on these

[17] The mean arterial blood pressure, also referred to as mean arterial pressure, is the average pressure within an artery over a complete cycle of one heartbeat. Masseter is one of the muscles of mastication located at the cheek.

findings, Emurian (1991, p. 305) concludes that “the strength of the variable SRT [system response time] condition was not potentiated in the present experiment by the avoidance incentive [the $10 with the risk of reduced earnings], at least in terms of producing a greater physiological response than the constant SRT condition. This suggests that the equivalent query productivity levels over time (i.e., work density), rather than SRT constancy or variability, was the active variable.”

With respect to the investigation of the eleventh subject, results indicate that responses of the cardiovascular system habituated over successive performance sessions; however, when new queries were introduced, heart rate increased, and even "exceeded the magnitudes observed during the first performance session" (p. 304). This result suggests that cardiovascular habituation may reverse under novel performance demands.

Another important finding of the study is that significant positive correlations were found among systolic, diastolic, and mean arterial blood pressures, and a positive relationship was also found between heart rate and masseter EMG responses (based on data from the performance sessions; the correlation matrix shows that the range of r was 0.66 to 0.83). This clearly indicates that different biological stress systems, both within a specific category (e.g., systolic, diastolic, and arterial blood pressures pertain to the cardiovascular system), as well as those across categories (e.g., cardiovascular reactions and muscle tension), are highly interrelated (see Figure 2).

Based on a similar experimental task, Emurian (1993) presents the results of a follow-up study. Unlike the first study, this experiment drew upon a mixed-gender sample, namely 16 males (mean age: 23.8 years; range: 19–49; SD: 7.1) and 16 females (mean age: 23.4 years; range: 19–42; SD: 5.9).

First, based on an average across all 32 participants, the results show that systolic and diastolic blood pressure, mean arterial blood pressure, heart rate, and masseter muscle EMG response were significantly higher in the performance session (database query task), if compared to baseline (resting with the possibility of reading). Thus, these findings indicate that human-computer interaction may significantly elevate biological parameters.

Second, with respect to gender differences, it was found that, unlike men, women under high levels of work pressure show higher masseter levels. Tension in this muscle may indicate “microaggressive” behavior, as well as “anger” (see the discussion in Emurian 1993, pp. 356-366). Consequently, one interpretation of this result is that if women carrying out a human-computer interaction task under time pressure are becoming angry, this, in turn, may also have effects on performance because the study found that females “showed higher overall error rates and longer task durations than the males” (p. 365).

Altogether, based on the two experiments, Emurian (1993) provides a clear-cut statement about his conclusions: “To the extent that VDT [video display terminal] operators in the workplace [today we would say computer users in organizational settings] show cardiovascular and mood changes in response to their work, these health-related themes have direct relevance to the potential long-term health consequences of VDT-based work. The present laboratory model and results indicate that cardiovascular and EMG effects of VDT-based work, programmed under time-pressured and motivated conditions emulating the workplace, are robust and dynamically sensitive to fluctuating performance demands. Evaluations of VDT operators’ physiological and mood status in the workplace are now indicated” (p. 368).

Another study (Trimmel et al., 2003) also investigated system response time. The investigation is based on the belief that long response times cause uncertainty, which leads to arousal, as well as to stress. A laboratory experiment was conducted, in which 25 Austrian students participated (age range: 20–30 years; 14 skilled and 11 unskilled Internet users; mixed-gender sample). Subjects had to answer questions that required a search for information on the Internet (e.g., booking a hotel).

In the study, system response times were grouped into three categories: short (2 seconds), medium (10 seconds), and long (22 seconds). The experiment was designed to detect changes in heart rate and skin conductance at three periods: the 10^{th} to 5^{th} second before the waiting time (baseline), during waiting (2, 10, or 22 seconds), and the 5^{th} to 10^{th} second after waiting (post-baseline). Furthermore, mental load was measured based on a 163-mm analog scale.

The results show significant biological stress responses. Specifically, it is reported that longer response times caused higher heart rates and enhanced electrodermal activity (while no significant differences were found between the baseline and post-baseline conditions). Importantly, this enhanced activity of the physiological parameters was found to be independent of expertise, indicating that no long-term habituation took place.

Moreover, the entire sample was split into two groups (based on cluster analysis): high and low mental load. Using this distinction, the authors found that individuals experiencing high mental load do have a higher overall heart rate (a heart rate of 114 beats per minute was observed for the 22-second condition).

Altogether, this study found that system-related interruptions may lead to notable stress responses, and that the finding is not related to Internet users' expertise. Interpreting their results, the authors hypothesize that the elevation of biological parameters such as heartbeat and skin conductance may reflect increased attention, as well as active mental performance, particularly because subjects might have given thought to potential reasons for delayed response times. Finally, in their recommentation for practice, the authors write that "short SRTs [system response times] should be provided for the Internet user. For cases in which a long SRT cannot be avoided, a coping mechanism, such as changing the focus of attention, could be suggested" (p. 620).

The Boucsein et al. research group has not only conducted field studies in the technostress domain (see Boucsein & Thum, 1997), but has also systematically studied the effects of the length and variability of system response time on biological parameters. Their work in this specific area has recently been described as "thorough" and "well-done" (Dabrowski & Munson, 2011), and their results have been judged to "show clear and convincing evidence that changes in SRT [system response times] cause direct changes in the physiological functioning of users" (p. 560). As a general rule, excessively long response times (though what is considered long is task-dependent) and/or a high degree of variability in response times may result in considerable biological stress reactions, such as an increase in skin conductance (e.g., Kuhmann et al., 1987).

Altogether, through the 1980s and 1990s this research group ran several corresponding laboratory experiments (based on hundreds of subjects). The results of these studies were recently summarized in a review (Boucsein, 2009), so all their studies are not discussed in detail here. Rather, the most important findings from this review are presented, concentrating on two classes of response times (short and long) that were studied under two different conditions (time pressure during the human-computer interaction task present, or absent).

For short response times (0.5–2 seconds) with time pressure, the following findings are reported: (a) systolic and diastolic blood pressure increases, (b) heart rate variability decreases, (c) respiration rate increases, (d) electromyography frontalis power increases (i.e., muscle tension on the forehead), and (e) frequency of nonspecific electrodermal responses increases; without time pressure, the results were : (a) systolic and diastolic blood pressure increases, and (b) heart rate increases.

For long response times (8 seconds or longer) with time pressure, the results are: (a) skin conductance level increases, (b) frequency of nonspecific electrodermal responses increases, (c) amplitude of nonspecific electrodermal responses increases, (d) systolic and diastolic blood pressure decreases, and (e) respiration rate decreases; without time pressure, the findings are: (a) amount of electrodermal activity increases, and (b) frequency of nonspecific electrodermal responses initially increases and later decreases.

To sum up, the pattern of biological responses to varying lengths of system response times, as well as their variability, is complex. Importantly, it is reported in the review that both the experience and expectations of a user, as well as the task at hand (e.g., data entry versus complex decision making) and context factors (e.g., time pressure), may have significant influence on physiological parameters.[18]

Boucsein (2009) also presents recommendations for determining the "optimal response time" for a given task based on biological, performance, and health measures. According to research findings of his group, the "optimum" is reached in a situation with the following properties: (a) no marked increases in cardiovascualr activity, (b) low frequency of nonspecific electrodermal responses, (c) no increased general muscle tension, (d) low reports of pain sympotms, and (e) good performance in the human-computer interaction task at hand. These guidelines may be used in pratice by managers and engineers to evaluate systems.

Endocrinological System

Seven technostress studies were identified in this category; five of them are field studies, while the remaining two are laboratory experiments.[19]

Field Studies

The two-stage field study by Johansson and Aronsson (1984) was discussed in the section addressing the effects of technostress on the autonomic and somatic nervous systems. In the second stage of the study, 11 users with extensive computer work and 10 individuals with a low level of computer work were investigated in detail (all female).

[18] Notably, in a study designed to observe data-entry tasks, Schleifer and Okogbaa (1990) found that heart rate and blood pressure did not vary significantly with slow or rapid response times.

[19] In this section, not only are stress hormones discussed; substances related to other systems, particularly the immune system, are also considered.

Altogether, the findings of their study show that stress (biological measures), as well as psychosocial stressors and symptoms (survey measures), were comparatively higher in the group of individuals with extensive computer work. Despite this general result, however, not all biological parameters showed an elevation as a result of extensive computer work. Specifically, in contrast to adrenaline, noradrenaline was not elevated.

This (counterintuitive) result is in line with findings from a study by Gao et al. (1990), who found, based on a student sample, that noradrenaline excretion in urine decreased after computer-based data entry work, while adrenaline excretion increased. Importantly, changes in noradrenaline excretion after human interaction with computers are possibly moderated by user age. One study (Tanaka et al., 1988) found that after two hours of computer work "noradrenaline excretion showed a tendency to decrease in the young group [comparable to the student sample in the Gao et al. study], a significant increase in the middle-aged and a tendency to increase in the elderly" (p. 1753).

As noted, during Johansson and Aronsson's (1984) investigation, an unplanned breakdown of the firm's computer system took place, and hence an "improvised mini-study" based on a sample size of six individuals was conducted. Despite this small sample size, however, the computer breakdown led to a significant increase in adrenaline levels, as compared to baseline values from the regular operation phase.

Moreover, this study also assessed the levels of triglycerides, a substance that is related to the development of cardiovascular symptoms and diseases (e.g., heart attack). The level of triglycerides was significantly higher in the group of individuals with extensive computer work, if compared to the group with a low degree of computer work, indicating the potential negative effects of stress in human interaction with ICT.

Johansson and colleagues conducted another field study in the 1970s (Johansson et al., 1978) with significant implications for modern ICT work, and in particular for computerized tasks with a high degree of monotony but requiring mental concentration (e.g., data entry in spreadsheet programs or enterprise systems). In essence, their theorizing is based on the notion that high degrees of mechanization and monotony of work (e.g., characterized by a low degree of job content variation in a human-machine context) increase stress and arousal, and this, in turn, negatively affects work satisfaction and health.

To test this hypothesis, Johansson et al. (1978) investigated 24 male workers in a Swedish sawmill. A group of 14 workers (mean age: 38.4 years; SD: 3.2) whose tasks were characterized by repetitiveness, physical constraint, and high demands for attention (a high-risk group) was compared to a control group of 10 workers (mean age: 37.6 years; SD: 2.7) who performed their work under more flexible conditions, characterized as "[w]ork pace [is] less dependent on technology" (p. 588), among other attributes. The data collected in the study (urine samples collected four times over the course of a day), both at work and during leisure, were adrenaline and noradrenaline levels, as well as self-ratings on mood and alertness.

The hormone results indicate that during work the high-risk group excreted more catecholamines (i.e., adrenaline and noradrenaline) than the control group. Specifically, a significant difference was found for adrenaline levels (based on the average across the four measurements). In contrast, the noradrenaline difference between the groups only showed a significant difference based on the last measurement (taken in the afternoon). Importantly, this finding indicates a high fatigue level at the end of a working day, and the authors write that "it usually takes [the workers from the high-risk group] an hour or two after work to get sufficiently relaxed for interaction with their family" (p. 591).

Also, catecholamine levels were correlated with task characteristics, specifically indicating that both adrenaline and noradrenaline levels are positively related to the degree of task repetitiveness, while noradrenaline levels were low for individuals who could move during work (i.e., less physical constraint).

Furthermore, based on a combination of self-reports and clinical tests, a significant difference was found regarding two health symptoms, namely headache and nervous disturbance (high-risk group > control group). This substantiates the belief that specific attributes of work, particularly monotony and mental overload that also play a significant role in several modern ICT tasks (e.g., data entry, Lundberg et al., 1993), may have detrimental effects on health. Interpreting their results, the authors write that the task "experienced by the high-risk group demands continuous mobilization of biochemical adaptive resources which in the long run may prove harmful to the individual … the risk group showed a higher frequency of psychosomatic illness and absenteeism than the control group" (p. 583).

One longitudinal field study (Korunka et al., 1996) investigated the effects of working with new computer technology on hormone levels. In addition to the hormone measurements, subjective perceptions of the strain levels of computer users were collected through a multi-item survey instrument. Measurements were taken at three points in time: at t_1, 2 months before the technology was implemented (baseline: either manual work or work with a legacy system); at t_2, during the implementation phase (i.e., 2–6 months after the implementation process began); and at t_3, 12 months after the implementation was completed. Both hormone and survey assessments were taken on work days and rest days to rule out the influence of this potential confounding variable. Data analyses are based on 14 male individuals (mean age: 29.3 years; age range: 24–38) from five different Austrian companies. Urine samples were used to assess three different stress hormones (adrenaline, noradrenaline, and cortisol).

The study results indicate that implementation of new computer technology was related to significant increases in catecholamines; this hormone category showed a monotonous increase from t_1 to t_3. Cortisol elevations, in contrast, were less evident; that is, even though the highest levels of cortisol were found at t_3, the t_1 level was higher than the t_2 level (based on the average values of work and rest days). Despite this lack of monotonous increase, however, even after implementation had been completed, cortisol excretion still tended to increase. Moreover, there was no difference between the hormone levels found on work days and rest days.

Reflecting on their results, Korunka et al. (1996, p. 449) write that “increased arousal was not restricted to the implementation period of the new technology but persisted even after the employees had adjusted to the novel work situation. The data suggest, therefore, that the altered job situation in itself is more demanding than the original work.” Moreover, the authors argue that increases in stress hormones after implementation of new computer technology are likely to occur because “the implementation process [is] considered to evoke insecurity, uncertainty … demanding reorientation” (p. 441).

Another important finding of this study is that there was only a “weak relationship” between subjective strain levels and hormone measurements (assessed based on multiple hierarchical regression analyses). The authors comment on this result, stating that they “failed to detect a link between subjective strain indicators and hormone levels, a finding that agrees with many other studies” (p. 450). Therefore, individuals are often not able to consciously perceive stress in their interaction with ICT, and this has a significant consequence: While stress hormones are already active in the body, individuals might not be aware of it. Only when these stress levels exceed a specific threshold, do people start to consciously perceive the stress (e.g., based on an intense heartbeat). This discrepancy between self-reports and biological measures may have detrimental health effects, because technostress countermeasures may not be implemented due to a lack of problem awareness.

Important contributions to biological technostress research were also made by Arnetz and colleagues. In one study (Arnetz & Berg, 1996), 47 office workers were investigated during a day of (a) regular work in front of a computer (VDU) and (b) leisure in the same environment.

The major objective of this study was to investigate possible effects of computer work on two hormones, namely melatonin and ACTH. Unlike ACTH, which plays a direct role in human stress reactions (see Figure 2), melatonin’s functions are not as directly related to stress. However, this substance, which is mainly produced in the pineal gland (an area located deep within the brain), has a number of positive functions, including regulation of the circadian rhythm, positive effects on the immune system, and protection against a wide variety of processes that damage tissue via free radical mechanisms (e.g., Reiter et al., 2000).

The Arnetz and Berg (1996) study reports that circulating melatonin levels decreased significantly during computer work, while ACTH levels increased significantly. In the leisure condition, no significant changes in melatonin and ACTH levels were found. These results indicate that computer work may reduce substances in the body that positively affect health (e.g., melatonin’s function as antioxidant), while they may increase substances that can negatively affect health (e.g., ACTH and resulting substances such as cortisol may negatively affect the immune and cardiovascular systems; McEwen, 2006).

Importantly, a link between melatonin, as well as ACTH and cortisol, is documented in the literature (e.g., Beck-Friis et al., 1985). Pathological activity of the HPA axis, of which ACTH and cortisol are major components (see Figure 2), is one important correlate of depression, and it was found that a specific form of depression is related to decreased levels of melatonin. The results reported in Arnetz and Berg (1996), therefore, are in line with these more general findings from endocrinological research, and they substantiate the notion of severe negative biological effects of technostress.

Furthermore, it is reported in the study that a subjective feeling of mental strain during work was positively correlated with circulating levels of ACTH ($r = 0.5$), but not with melatonin, and regression analyses reveal that occupational mental strain explains 22% of the variance in ACTH levels during work (Arnetz and Berg, 1996, p. 1109).

In another longitudinal study of this research program, Arnetz (1996) investigated the impact of a controlled stress-reduction program on perceived mental stress and specific biological measures (see also Arnetz & Wiholm, 1997). A total of 116 workers (“highly skilled professionals, such as telecommunication systems design engineers,” p. 54) from a Swedish technology firm participated in the study. Employees from one department served as the intervention group, and members of another comparable organizational unit served as the control group. Individuals in the intervention group selected one of three different stress management techniques: progressive relaxation, applied relaxation, or Tai Chi.[20]

The individuals in the intervention group were offered a once-weekly, three-month-long training period that was led by experienced personnel (note that the subjects participated "in between half and three quarters of all the training sessions"). Measurements, both survey and biological assessments, were taken at three points in time, namely, at t_1, before the start of the intervention program, at t_2, three months after the end of the program, and at t_3, five to six months after t_2.

The following biological substances were determined in the study: thrombocytes, white blood counts, hemoglobin, blood glucose, cortisol, testosterone, cholesterol, prolactin, apolipoprotein A_1 and B, fructosamine, and albumin. Significantly, this was the largest number of substances determined in any study reviewed for this article. An extensive reflection on all results is beyond the scope of this article, so the discussion is limited to two substances that have not yet been addressed in this article—prolactin and thrombocytes.[21]

The results indicate that a significant improvement occurred in the intervention group (type of stress-reduction program and intensity of participation did not substantially influence the results). Biologically, it was found that circulating levels of the stress-sensitive hormone prolactin decreased in the intervention group, and a reduction in mental strain was also observed.

These research findings, published in the 1990s, achieve further relevance from recent evidence demonstrating significant elevations of prolactin as a consequence of the perception of an acute stressor. In one study (Lennartsson & Jonsdottir, 2011), 30 men and 15 women (age range: 30–50 years) underwent the TSST. Based on blood samples, it was found that prolactin levels increased significantly (if compared to the baseline measurement), along with notably elevated plasma ACTH, serum cortisol, and heart rate, as well as systolic and diastolic blood pressure. While the magnitude of the prolactin response was significantly correlated with the magnitude of the response of the HPA axis, the correlation was less pronounced, but still existing, in the cardiovascular responses. Thus, due to this recently established relationship of prolactin with several other biological stress systems, the findings reported in Arnetz (1996) take on new meaning.

Another highly interesting biological result reported by Arnetz (1996) is that circulating thrombocytes decreased significantly in the intervention group (these are specific cell fragments in the body). If the number of thrombocytes is pathologically high, increased risk for thrombosis (i.e., clot in a blood vessel) exists, and this may result in pulmonary embolism, stroke, or other serious or life-threatening condition.[22]

It is of critical value, however, to recognize that it is logically invalid to deduce a reverse effect from the findings of Arnetz (1996)—that technostress increases the number of thrombocytes. Further research is needed here. However, if support for this hypothesis had been found (i.e., technostress→ thrombocytes), a further significant link between technostress and negative health implications would have been established.

Altogether, as a concluding statement on the results of his research program on technostress, Arnetz (1996) writes that the "findings need to be taken into consideration as new developments in the IT area rapidly transcend into everyday workplaces. Correctly designed and implemented, along with proper organizational adaptations, such technologies will add significantly to enhance work and business opportunities … if due consideration is not given to human factor needs, we will continue to see a number of undesirable health consequences" (p. 64).

Laboratory Experiments

In the most recent study of this review, Riedl et al. (2012) investigated whether system breakdown—one of the most prevalent acute stressors in human-computer interaction—increases users' levels of the stress hormone cortisol. This study is of particular significance (as is indicated by the authors in the article) because, until their research, technostress research had not investigated system breakdown, under controlled laboratory conditions and based on salivary cortisol assessments. Their research used a computer system breakdown in the form of a pop-up

[20] The difference between progressive and applied relaxation is that the latter focuses on teaching an individual to reach the relaxed mood very quickly, and thus prevent psychophysiological activation; Tai Chi is a Chinese technique that emphasizes concentration on the execution of controlled motions while keeping the mind focused on those motions; Arnetz, 1996, p. 55).

[21] Despite this focus, however, the observation that cortisol increased over time, but that there was no difference between the two groups, is a significant result. Testosterone, in contrast, decreased over time, with the lowest values at t_3, and with a tendency for a higher mean level for the intervention group.

[22] If the number of thrombocytes is pathologically low, the risks include substantial risk for bleeding.

error message. The researchers embedded the stressor into an online shopping user interface, which they developed from scratch for the experiment. In this way they were able to rule out the possibility that experience with a specific interface could influence the results. The task for the participants was to search for specific products and to put them into the online shopping cart, but had no time pressure for completing the task. Subjects were told that the objective of the experiment was to study the usability of the online shop.

From a theoretical viewpoint, it is important to note that cortisol elevations usually occur if (a) goals are threatened, (b) the situation is uncontrollable, and/or (c) task performance could be negatively judged by others, referred to as social evaluative threat (Dickerson & Kemeny, 2004). The Riedl et al. experiment was designed to meet all three conditions.

Based on a between-subjects design, 20 male individuals participated in the study (mean age: 24.7 years; SD: 5.5). Each subject was randomly assigned either to the treatment group (10 subjects, with system breakdown) or the control group (10 subjects, no breakdown). Two cortisol measurements were taken in each group, one at the beginning of the experiment and, therefore, before the completion of the task (baseline), and one afterwards, which was collected 25 minutes after the baseline measurement, because cortisol elevation does not occur instanteanously after stimulus onset (e.g., Dickerson & Kemeny, 2004).

The results of the study indicate that (a) the baseline cortisol levels, both in the control and treatment groups, were within the normal concentration range of healthy individuals, (b) there was no significant difference between the average baseline cortisol levels in the control and treatment groups, (c) after system breakdown, the cortisol level in the treatment group increased sharply, while in the control group, in which no system breakdown occurred, no such increase could be observed, and (d) the cortisol increase is statistically significant in the treatment group.

Moreover, by contrasting their results with a meta-analysis that includes 208 cortisol studies based on various stressor types such as public speaking, cognitive tasks, or noise exposure (Dickerson & Kemeny, 2004), Riedl et al. conclude that ”the present study shows that system breakdown in the form of an error message is an acute stressor which may elicit cortisol elevations as high as in non-HCI stress situations such as public speaking (e.g., Trier Social Stress Test)“ (p. 66). This research result is not only of practical relevance. Rather, it is of particular theoretical importance because, before the study, it was unclear whether biological stress reactions in human-computer interaction resemble those in human-human interaction.

In addition to endocrinological measures (particularly stress hormones such as adrenaline, noradrenaline, and cortisol), research also studied biological stress reactions based on substances related to the immune system, as already outlined in the example of Arnetz and Berg (1996), who investigated, for example, melatonin.

Another important substance for the functioning of the human immune system is immunoglobulin A (IgA). Among its other functions, this substance protects the organism against specific negative effects of bacteria and viruses (e.g., Jemmot & McClelland, 1989), and in the case of being IgA deficit, an individual is at risk for immuno-deficiency (e.g., Nomura, 2006). Moreover, research indicates that salivary IgA increases immediately after brief exposure to a stressor (”immediate stress effect”), while it usually decreases several days after stress (”delayed stress effect”) (Nomura, 2006; Tsujita & Morimoto, 1999).

Against the background of this knowledge on IgA, Nomura et al. (2005) investigated in a laboratory setting (a) whether engagement in a human-computer interaction task affects IgA levels, and (b) if so, whether exposure to pleasant music can alter this effect.

Six healthy Japanese students participated in the study (all male, age range: 25–33 years), based on a within-subjects design. The subjects had to perform a computer-based calculation task. Specifically, they were ”instructed to conduct an addition of two succeeding numbers from end to end inputting each answer by keyboard” (Nomura et al., 2005, p. 132); this procedure was repeated multiple times, based on varying initial numbers. The participants were instructed to perform the calculations as fast as possible. The authors used this task because it induces ”mental stress,” as it is ”repetitive, boring and endless” (p. 132). This task lasted thirty minutes for each subject. After that, each subject was exposed for seven minutes to (a) music (”slow tempo, instrumental, and not too much inflection,“ p. 132), (b) noise, or (c) rest in a silent dark room. The substance IgA was measured based on salivary assessments, which were taken at t_1 (before the human-computer interaction task began), t_2 (after thirty minutes when the task was completed), and t_3 (after the seven minutes' exposure to one of the treatments).

The results of the study show that salivary IgA levels significantly increased from t_1 to t_2. Moreover, the findings indicate that IgA concentration decreased from t_2 to t_3 in 15 out of 18 cases (6 subjects × 3 conditions). Importantly, it was also found that the level of IgA decrease after music was significantly higher than in the other two conditions, and the authors stress that in the ”music condition,“ IgA levels decreased nearly to baseline within the seven minutes. Building on these results, the authors write that salivary IgA is a ”useful mental stress and relaxation index,“ and it can be applied for ”improving an office work environment with VDT [visual display terminals] and stress management.” Altogether, this study is in line with the well established notion that pleasant music can ameliorate biological stress parameters (e.g., Knight & Rickard, 2001; Pelletier, 2004).

Summary

Table 2 summarizes the biological investigations of technostress, and groups them into four categories—genetic system, central nervous system, autonomic and somatic nervous systems, and endocrinological system. Studies in the latter two categories are further grouped into field studies and laboratory experiments.

The results presented, in general, demonstrate notable negative biological effects of both acute and chronic ICT stressors.[23] Specifically, the review identifies three major results:

- With respect to the four biological levels of analysis, an imbalance in research intensity exists; while the levels of the autonomic and somatic nervous systems and the endocrinological system have been studied intensively, technostress research related to the genetic system and the central nervous system hardly exists.
- Both field studies and laboratory experiments show that human interaction with computers in general, as well as perception of specific annoyances or problems (e.g., long response times, system breakdown), often result in elevations of skin conductance, blood pressure, heart rate, and stress hormones, particularly adrenaline and cortisol—a fact that may have detrimental effects on both health and performance. In line with the potential negative health effects, human-computer interaction has also been shown to reduce the levels of substances in the human body that may positively affect the functioning of the immune system (e.g., melatonin).
- Evidence exists that countermeasures such as well-designed breaks during computer work, ”user-friendly” implementation strategies, regular execution of relaxation techniques, and pleasant music can positively affect biological parameters. Specifically, these countermeasures have been shown to lead to reductions in skin conductance, blood pressure, heart rate and heart rate variability, and substances related to the cardiovascular and immune systems (e.g., thrombocytes, prolactin, immunoglobulin A).

[23] Only two studies were identified in which technostress was reported to have no effect on the elevation of stress hormones. In one laboratory experiment (Ekberg et al., 1995), 30 subjects (20 females, 10 males) had to perform a stressful computer-based data entry task, and results showed that adrenaline and noradrenaline in urine were unaffected; similar results are reported in Gao et al. (1990). Importantly, despite the fact that stress hormones were not elevated in the Ekberg et al. experiment, the study found significant increases in other biological measures (heart rate and activity in the trapezius muscles of the neck and shoulder). As well, subjects who had carried out the stressful computer-based data entry task reported in a post-experiment survey that they “felt more activated” and that “pain and discomfort from the stomach increased” (p. 475).

Research Agenda

This section presents a detailed research agenda with the goal of advancing the current understanding of technostress. By framing the research agenda to reflect the unanswered research questions and underrepresented topics (as were identifed in the literature review), the structure herein presents three major domains:

- Theory and methods
- Design science and engineering
- Health and coping strategies.

Theory and Methods

The literature review indicates that the literature has addressed the four primary biological levels of analysis with varying levels of intensity. Specifically, while the effects of technostress on the autonomic nervous and endocrinological systems have been studied extensively, relative to the other biological levels of analysis (see the summary in Table 2), the relationships between technostress and the genetic and brain levels of analysis have received no significant attention in the literature.

With respect to genetics, only loosely related topics have been addressed, such as research (presented in this paper) on the relationship between specific gene networks and personality traits such as neurocitism (e.g., Canli, 2009; Caspi et al., 2003). As well, the relationship between specific gene variants (e.g., BDNF gene) and reactivity of the HPA system (e.g., Shalev et al., 2009) has been the subject of research.

Table 2. Summary of Literature Review

Study	Major Findings
GENETIC SYSTEM (Number of identified studies: 0 → 0%)	
CENTRAL NERVOUS SYSTEM (Number of identified studies: 1 → 6%)	
Trimmel & Huber (1998) - Paper/Pencil Tasks versus HCI Tasks - Austria - *N*=49 (21F, 28M) - Student Sample	The P300 amplitude, a measure that is based on EEG, was smaller after HCI tasks, if compared to paper/pencil tasks, indicating that HCI led to fatigue. This neuronal after-effect of HCI was independent of a user's computer experience.
AUTONOMIC AND SOMATIC NERVOUS SYSTEMS (Number of identified studies: 7 → 47%)	
Field Studies	
Johansson & Aronsson (1984) - 1 Organization - Sweden - *N*=21 (21F) - Urine Samples	Extensive computer work increased blood pressure and heart rate. Breakdown of a computer system increased diastolic blood pressure (*N*=6).
Boucsein & Thum (1997) ● - 1 Organization - Netherlands - *N*=11 (1F, 10M)	During complex computer-based work, short breaks were more effective in facilitating recovery from mental strain (reduced heart rate variability), as well as emotional strain (reduced electrodermal activity), until the early afternoon. Longer breaks were more effective in lowering emotional strain in the late afternoon. Physical strain (neck electromyogram) increased as a result of computer system breakdown.
Wastell & Newman (1993, 1996a, 1996b), Wastell & Cooper (1996) ● - 1 Organization - Great Britain - *N*=18 (mainly F)	The elevation of systolic blood pressure with increasing workload was steeper for a paper-based system than for a new computer system, which was characterized by a high degree of perceived usefulness and for which the implementation was based on a "user-centered" approach.
Laboratory Experiments	
Emurian (1991) - Database Query Task - USA - *N*=11 (11M) - Student Sample	Systolic blood pressure, mean arterial blood pressure, and heart rate were significantly higher during human-computer interaction, if compared to a baseline resting condition, while diastolic blood pressure and masseter muscle EMG response were not. System response time variation had no effect on the biological measures.
Emurian (1993) - Database Query Task - USA - *N*=32 (16F, 16M) - Student Sample	Systolic and diastolic blood pressure, mean arterial blood pressure, heart rate, and masseter muscle EMG response were significantly higher during a human-computer interaction task, if compared to a baseline resting condition. Women, unlike men, showed increased masseter muscle EMG levels under high working pressure, possibly indicating anger and "microaggressive" behavior.
Trimmel et al. (2003) - Information Search Task (Internet) - Austria - *N*=25 (Mixed- Gender Sample) - Student Sample	Longer system response times caused higher heart rates and enhanced electrodermal activity. This enhanced activity of the physiological parameters was independent of expertise, indicating that no long-term habituation took place. A correlation between self-reported strain (mental load) and heartbeat was found.

Table 2 Continued. Summary of Literature Review	
Boucsein (2009) - Human-Computer Interaction Tasks (German Subjects) - Review of 6 experiments (Total *N*=242)	The pattern of biological responses to varying length of system response times, as well as their variability, depended on a multitude of factors (e.g., user characteristics, task, as well as time pressure). In general, there seems to be a tendency for long and varying response times to elevate blood pressure, heart rate, and specific EMG responses.
ENDOCRINOLOGICAL SYSTEM (Number of identified studies: 7 → 47%)	
Field Studies	
Johansson & Aronsson (1984) - 1 Organization - Sweden - *N*=21 (21F) - Urine Samples	Extensive computer work increased adrenaline and triglycerides, but not noradrenaline. Breakdown of a computer system increased adrenaline (*N*=6).
Johansson et al. (1978) - 1 Organization - Sweden - *N*=24 (24M) - Urine Samples	Monotonous, repetitive, machine-dependent, and mentally demanding work increased adrenaline levels and incidence of headache and nervous disturbance, but it did not affect noradrenaline.
Korunka et al. (1978) - 5 Organizations - Austria - *N*=14 (14M) - Urine Samples	The implementation of new computer technology resulted in elevations of both adrenaline and noradrenaline and, to a lesser degree, also in elevations of cortisol. Subjective perceptions of users' strain levels (survey) were only slightly correlated with stress hormone levels.
Arnetz & Berg (1996) - Organizational Setting* - Sweden - *N*=47* - Blood Samples	Computer work resulted in decreased melatonin and increased ACTH. Mental strain during work (survey) was positively correlated with levels of ACTH, but not with melatonin.
Arnetz (1996) ● - 1 Organization - Sweden - *N*=116 (25F, 91M) - Blood Samples	Computer workers who participated in a stress management program had decreased levels of prolactin and thrombocytes, as well as lowered levels of mental strain (survey). The stress management program had no effect on cortisol.
Laboratory Experiments	
Riedl et al. (2012) - Online-Shopping Task - Austria - *N*=20 (20M) - Student Sample - Saliva Samples	Breakdown of a computer system in the form of a pop-up error message significantly increased users' cortisol levels. System breakdown is an acute stressor which may elicit cortisol elevations as high as in non-HCI stress situations such as public speaking.

Table 2 *Continued*. Summary of Literature Review	
Nomura et al. (2005) ● - Computer-Based Calculation Task - Japan - *N*=6 (6M) - Student Sample - Saliva Samples	Immunoglobulin A (IgA) increased after a computer-based calculation task. IgA decreases, however, were more pronounced after exposure to pleasant music, if compared to noise exposure or resting in a silent dark room.

Notes: F: Female, M: Male, EEG: Electroencephalography, EMG: Electromyography, HCI: Human-Computer Interaction. Sample characteristics are reported in the level of detail as is available in the studies. The "●" symbol indicates that a study investigated a technostress countermeasure. The asterisk (*) in the Arnetz & Berg (1996) study indicates that the number of investigated organizations, as well as the gender distribution in the sample, are not reported in the study. The six investigations reviewed by Boucsein (2009) are: Schäfer et al. (1986, *N*=20), Kuhmann et al. (1987, *N*=68), Kuhmann (1989, *N*=48), Kuhmann et al. (1990, *N*=24), Thum et al. (1995, *N*=40), and Kohlisch & Kuhmann (1997, *N*=42).

However, in order for technostress research to progress, more direct investigations into the genetic foundations of this phenomenon are necessary. Against this background, addressing the following research questions in future investigations is likely to be fruitful:

1. *What percentage of the variance in (a) biological technostress reactions (e.g., hormone excretion) and (b) self-reported technostress perceptions can be explained by genetic factors, environmental factors, or a blend of both?*
2. *Are specific gene networks associated with biological technostress reactions?*

At first glance, IS scholars might perceive these and similar research questions to be unusual. At the very least they represent new research territory. However, answers to these and similar questions are of paramount importance for progress in the field (Riedl et al., 2010a), and the fact that their investigation applies innovative research methods—methods unfamiliar to most IS scholars—does not diminish the value of the process and results for the IS community. Rather, in order to study these questions, it may be beneficial for IS scholars to team up with academics in other disciplines (e.g., neurobiology or psychology), who are familiar with these methods. Among the methods that will be of benefit are twin study approaches, molecular genetic studies, and imaging genetic investigations (e.g., Casey et al., 2010; Johnson, 2007).

It is significant to note that in the field of economics, as well as other business and management disciplines, similar questions have already begun to be the subject of research, which provides a promising starting point for IS scholars. These investigations have applied the twin study approach (refer to this paper's section on the biological foundations of stress). Zyphur et al. (2009), for example, have studied the genetics of economic risk preferences. Cesarini et al. (2010) analyze genetic variation in financial decision making. To provide examples from marketing, Simonson and Sela (2011) investigated the heritability of consumer decision making, and Bagozzi et al. (2012) explored genetic and neurological foundations of customer orientation. Studies such as these underscore the value of the genetic foundations of IS constructs—with technostress as the representative model—as a major avenue for future IS research.

In addition to the call for future investigations into the relationship between technostress and genetics, it is likewise important to point out the importance of studies on the relationship between technostress and brain mechanisms. The only such study that was located in the literature is the EEG study by Trimmel and Huber (1998), who used voltage fluctuations on the scalps of users to show that human-computer interaction leads to fatigue. This experiment is a promising starting point, and deserves to be expanded in future research.

Moreover, IS scholars should consider research published in the field of *neuroergonomics*, a scientific discipline that studies the "human brain function in relation to work and technology" (Parasuraman, 2003, p. 5). A recently published book chapter on the concept of stress in neuroergonomics (Hancock & Szalma, 2008) presents a useful introduction to an area of research with the potential for profitable academic response.

As indicated in our previous discussion on the biological foundations of stress, activity in specific brain areas (e.g., hypothalamus, amygdala) is closely related to stress perceptions and reactions. From this research base, a number of questions arise that prompt future investigations:

3. *Which brain areas in computer users are specifically associated with technostress perceptions?*

4. *Do different stressor types (e.g., slow response time, system breakdown) lead to differential activation patterns in these brain regions?*
5. *How do different technostress countermeasures (e.g., availability of a reliable help desk) affect these brain activation patterns?*
6. *Do chronic ICT stressors (e.g., implementation of enterprise systems over the course of years) lead to structural changes in users' brains?*

It is important to note that a vast amount of neuroscience theories, methods, and tools for investigating these and similar questions exists. Several have recently been reviewed by Riedl (2009), Riedl et al. (2010a), Dimoka et al. (2011), and Dimoka et al. (2012). Moreover, it has already been shown that powerful tools such as functional magnetic resonance imaging (fMRI) can be applied to study IS phenomena. For example, Riedl et al. (2010b) applied fMRI as a mechanism to investigate online trust. These articles, along with the strong body of cognitive neuroscience literature, serves as a useful entry point for IS scholars who are interested in pursuing research on the relationship between technostress and brain mechanisms.

With respect to the insights to be gained from brain imaging studies, Dimoka et al. (2011) analyzed the cognitive neuroscience literature to propose a set of seven opportunities that IS researchers could pursue in order to inform IS phenomena. These opportunitites are (1) localizing the neural correlates of IS constructs (e.g., technostress), (2) capturing hidden mental processes, (3) complementing existing sources of IS data with brain data, (4) identifying antecedents of IS constructs, (5) testing consequences of IS constructs, (6) inferring the temporal ordering among IS constructs, and (7) challenging assumptions and enhancing IS theories.

From a theoretical viewpoint, it is also essential to highlight the critical role of moderating variables in technostress research. Figure 1 specifies a basic theoretical mechanism that describes causal relationships beginning at the perception of ICT stressors, and corresponding antecedent variables (e.g., computer self-efficacy), to possible negative performance and productivity effects. Importantly, it has been argued in this article that the activation of biological stress systems (e.g., release of stress hormones or elevations in skin conductance and blood pressure) and resulting states of well-being and health mediate the relationship between ICT stressors and performance/productivity outcomes.

However, one major variable category in Figure 1—the moderating variables—deserves special attention, as these variables may significantly alter the influence of ICT stressors on the activation of biological stress systems. As already outlined (based on the discussion of related work in the IS field), behavioral technostress research has revealed a number of moderators such as age, gender, and computer expertise (see Table 1).

Importantly, research has already provided significant insight into the biological bases of these and other moderator variables. As an example, the fact that brain anatomy and functionality change as a person moves from childhood, to adolescence, to adulthood, and particularly into advanced age (e.g., Spear, 2000), is a well-established concept in the brain sciences. Similarly established are findings about brain and hormone differences between women and men (e.g., Cahill, 2006), which is a phenomenon that has already been investigated in the IS context (Riedl et al., 2010b). Cognitive neuroscience, as well, provides significant evidence that, for a large number of tasks, the structure and functionality of the brain may differ substantively between experts and novices (Hill & Schneider, 2006).

Against this background, addressing the following topic signifies an important avenue for future IS technostress research:

7. *A need exists for IS scholars to contribute to the development of a taxonomy specifying established biological differences (e.g., hormone differences) in characteristics of the moderating variables (e.g., female versus male) that have been shown by behavioral research to influence technostress perceptions and reactions.*

The importance of this research originates from the fact that such a taxonomy makes possible a deeper understanding of *why* specific effects take place on a behavioral level. For example, research (Taylor et al., 2000) shows that oxytocin, a hormone related to activation in stress-relevant brain areas (e.g., amygdala), underlies a specific behavioral pattern in stress situations that is referred to as "tend-and-befriend." The study found that women, particularly—unlike men—follow this pattern in stress situations. Tending mainly involves nurturant activities that are important to protect the self and offspring, thereby reducing stress; befriending refers to the establishment and maintenance of social networks that may provide support for tending. Men, in contrast, are more prone to follow a "fight-or-flight" response in stress situations—a reaction that has, biologically, a stronger association with adrenaline excretion than with oxytocin release.

Design Science and Engineering

Serving the purpose of successfully establishing design science and corresponding engineering initiatives in the IS discipline (e.g., Gregor & Jones, 2007; Hevner et al., 2004; Walls et al., 1992), it is essential to outline the opportunities presented by biological stress research for the development of ICT artifacts.

One important field with possibilities for future activity is investigation into the stress-reducing potential of design elements on user interfaces (e.g., information presentation modes, colors, buttons, avatars, and navigation). Empirical research could investigate the effects of manipulation of the design elements on both biological parameters and self-reports, which would prompt research questions such as the following:

8. *Which design elements of user interfaces are most effective in reducing users' stress perceptions?*

9. *Is there a relationship between stressor type (e.g., slow response time, system breakdown) and the stress-reducing effectiveness of specific design elements (e.g., communication of an error message via a simple text-message or an avatar)?*

In addition to this potential stream of future IS design science research, another design science domain that could become important in future IS research is monitoring computer users' stress states in order to alert the user of risk, or to adapt the user interface in response.

Scientists and engineers, particularly in the field of *affective computing* (e.g., Picard 1997, 2003), have demonstrated, based on system prototypes, that bio-signals indicating a computer user's unconscious stress state (e.g., skin conductance or pupil dilation; see Figure 2) is one factor that can be constantly monitored during human-computer interaction, so that the user can be alerted to his or her stress state, or even can be prompted to directly adapt the user interface in real-time (e.g., changes in the information presentation mode). Basically, the goal is a reduction of stress perceptions, and this, in turn, may positively affect well-being and the resulting behavioral performance.

The following report about a joint development project of Philips and ABN AMRO (a large European bank) provides an example demonstrating the potential of using bio-signals for design science initiatives.

In 2009, the two firms of Philips and ABN AMRO presented a system prototype referred to as "Rationalizer." This system is "an emotion mirroring system for online traders" (Iske et al., 2009). Increasingly more private investors trade securities via the Internet. Empirical evidence shows, however, that financial decisions are suboptimal if an investor is stressed or emotionally aroused (Lo & Repin, 2002). For example, investors often sell too hastily when stock prices fall, because they are driven by fear and stress (Iske et al., 2009). With such behaviors in mind, Philips and ABN AMRO developed a system prototype that continuously measures the stress levels of an online investor based on galvanic skin response (GSR), using sensors that are attached to a user's wrist. The more stressed a person is, the more sweat is produced, which in turn increases the conductance of the skin. If a high stress level develops, the system's warning mechanism can create an alert that helps the investor abstain from financial transactions at a time that poses more risk. The primary purpose of the system is to reduce unfavorable financial decisions.[24]

In addition to GSR, a system may also recognize via eye-tracking technology that a user is stressed, because in such a situation the pupils dilate (see Figure 2). This biological stress reaction, which is mediated by activity in the sympathetic division of the autonomic nervous system, occurs automatically, and therefore the reaction does not reach the level of consciousness. Importantly, the correlation between pupil dilation and stress perception can be used to adjust a user interface in real-time to reduce the perceived level of stress, as already demonstrated by Zhai et al. (2005). Specifically, stress reduction could be accomplished by reducing the total amount of information presented on the screen or by changing the information presentation mode from textual to spatial.[25]

Altogether, it has been argued that such "intelligent systems" (independent from the specific biological measure on which they are based) may increase a user's well-being, which in turn may positively affect performance and productivity in human-computer interaction (Parasuraman & Wilson, 2008; Picard, 2003). Against this background:

10. *Design science researchers could contribute to the development of information systems, which use bio-signals as real-time system input in order to make human-computer interaction less stressful, and hence more convenient, enjoyable, and effective.*

Research in the fields of affective computing, brain-computer interaction, and neuroergonomics has already contributed substantially to this topic. Thus, IS research should draw upon knowledge from these reference disciplines. A promising starting point could

[24] The literature includes reports of computer mouse prototypes that have integrated sensors to automatically measure skin conductance during human-computer interaction, for the purpose of real-time stress management (e.g., Stockinger, 2004, 2005). In this context, see also biofeedback systems.

[25] Another promising technology could be based on the processing of facial information, because muscle activity in the human face is related to perceptions of emotions and stress, as is indicated in Figure 2. For further details, see, for example, Ekman (1982) and Knutson (1996), as well as the computer program FaceReader™ (www.noldus.com).

be to read introductory and overview papers in these disciplines. The following articles can provide a first set of meaningful insights (title, publication outlet, year of publication):

- Affective computing: Challenges, *International Journal of Human-Computer Studies*, 2003
- Affective computing: A Review, *LNCS 3784*, 2005
- Affect detection: An interdisciplinary review of models, methods, and their applications, *IEEE Transactions on Affective Computing*, 2010
- Brain-computer communication: Unlocking the locked in, *Psychological Bulletin*, 2001
- Brain-computer interfaces for communication and control, *Clinical Neurophysiology*, 2002
- Current trends in hardware and software for brain-computer interfaces (BCIs), *Journal of Neural Engineering*, 2011
- Neuroergonomics: Research and practice, *Theoretical Issues in Ergonomics Science*, 2003
- Putting the brain to work: Neuroergonomics past, present, and future, *Human Factors*, 2008
- Neuroergonomics: Brain, cognition, and performance at work, *Current Directions in Psychological Science*, 2011.

Health and Coping Strategies

Human health and well-being are major outcome variables in several scientific disciplines, including psychology, and especially medicine. Also, the health implications of human interaction with ICT should be a major topic in IS research, not only because human health itself is of paramount importance, but also because well-being and health have significant influence on work performance and productivity.

The health implications of ICT-related stressors (e.g., long and variable system response times, feelings of uncertainty due to changed workflows associated with the implementation of an enterprise system) have been the subject of intensive discussions several decades ago. In the 1990s, for example, Weil & Rosen (1997, pp. 5-6) wrote in their book on technostress: "It is important to recognize that the seemingly tiny frustrations that people experience every day have a cumulative negative impact on psychological and physical health … Blood pressure rises, sleep is disrupted, and people slug down tablets."

Altered levels of biological parameters such as blood pressure, heart rate and, especially, circulating stress hormones can have detrimental health effects, particularly over the long term. For example, the following consequences are among those reported in the scientific literature: insomnia, migraine headaches, depression, burnout, bronchial asthma, abdominal obesity, chronic hypertension, coronary heart disease, suppressed immune function, and cancer (e.g., De Kloet et al., 2005; Lundberg & Johansson, 2000; McEwen, 2006; Melamed et al., 1999; Walker, 2007). Accordingly, the measurement of biological parameters in order to objectively determine technostress levels is critical, because it makes more reliable predictions of future health states possible.

To date, however, research has derived the potential negative health consequences based on *syllogism*, and not original empirical investigations, as is explained in the following example.

<u>Empirical Finding 1:</u> Computer system breakdown, one of the most prevalent acute stressors in human interaction with ICT, may cause significant elevations of the stress hormone cortisol (Riedl et al., 2012).

<u>Empirical Finding 2:</u> Continually increased cortisol levels may lead to severe diseases such as chronic hypertension, coronary heart disease, or suppressed immune function (e.g., McEwen, 2006).

<u>Deductive Reasoning:</u> Repeatedly experiencing system breakdowns may lead to severe diseases in computer users.

Though this kind of deductive reasoning is important in order to derive hypotheses, it cannot substitute for original empirical research.

Against this background, a call is made for future investigations into the negative health effects of human interaction with ICT. The following research questions could be addressed in those studies:

11. *Is the intensity of objectively measurable interactions with ICT (e.g., assessed by the number of daily hours using computers or mobile phones) a predictor of (a) the number of days of sick leave used, (b) the probability of specific diseases (e.g., cardiovascular or neural diseases, immune function deficits, as well as cancer), and (c) average age at death?*
12. *Is the number of perceived ICT stressors (e.g., computer malfunctions) a predictor of (a), (b), and (c)?*

The existing IS literature on technostress (see Table 1) may serve as a valuable basis for investigation into the health effects of human interaction with ICT. Tarafdar et al. (2011), for example, identified five categories of technostress creators: techno-overload ("too much"), techno-invasion ("always connected"), techno-complexity ("difficult"), techno-insecurity ("uncomfortable"), and techno-uncertainty ("too often and unfamiliar"), each of which may have different health implications.

However, based on the research questions (11) and (12), the following third question can be raised:

13. *What are the costs for the health care system due to technostress?*

Reliable statistics on the costs of technostress for organizations and for society in general are not available. However, statistics on work stress show that the costs for the health care system are immense. The Prima-ef Consortium (a WHO-related organization), for example, reported in 2008 that work stress costs about 3-4% of the GNP in Europe; moreover, it is reported that "work-related stress is among the most commonly reported causes of illness by workers … affecting more than 40 million individuals across the European Union" (Prima-ef Consortium, 2008, p. 1). *The American Institute of Stress* (www.stress.org) and *The International Stress Management Organization* (www.isma.org.uk) report similar numbers. Against this background, it is essential that future studies seek to specify the costs of technostress.

With respect to determining the health implications of technostress, biological measurement is indispensable. Empirical evidence shows that *conscious* stress perceptions of humans, measured by means of self-report instruments (e.g., perceived stress scale, PSS, Cohen et al., 1983), often do not correlate with the usually *unconscious* elevations of stress hormones (Van Eck et al., 1996; Vedhara et al. 2000, 2003). This finding, reported in the literature on general stress research, has been replicated in several technostress studies that combine biological and self-report measures (e.g., Hjortskov et al., 2004; Korunka et al., 1996; Tams, 2011).

Importantly, given the possible detrimental health consequences of technostress, the question for effective coping strategies arises (e.g., Carver et al., 1989; Cohen, 1984). Two broad categories of strategies exist: problem-focused and emotion-focused (e.g., Lazarus and Folkman 1984). While the former strategy seeks to alter the person-environment realities associated with a stressful situation, the latter attempts to reduce negative emotions by altering the appraisal of a given stressful situation. Increasing computer knowledge to elevate the controllability of possible ICT malfunctions (such as system breakdowns or slow response times) is an example of a problem-focused strategy, while downplaying the potential negative effects that an ICT problem will have on accomplishing a goal (e.g., a specific task in an organizational context) is an example of an emotion-focused strategy (Hudiburg and Necessary 1996).

The literature review of this present paper has already revealed that specific coping strategies, or organizational countermeasures, may positively affect stress perceptions and reactions. It was found, for example, that professionally organized stress management programs such as relaxation techniques (Arnetz, 1996), well-designed breaks from work at computers (Boucsein & Thum, 1997), implementation strategies that prepare employees for business process changes (Wastell & Newman, 1993, 1996a, 1996b; Wastell & Cooper, 1996), and pleasant music (Nomura et al., 2005) can positively affect biological parameters, including reduced levels of stress hormones and reduction of cardiovascular activity.

However, in addition to these countermeasures, a large number of other potential measures exist as well (e.g., a help-desk service with exactly specified service levels that is available for users to call when they experience a specific ICT problem). Importantly, IS technostress investigations that rely solely on perceptual measures (see Table 1) have revealed several countermeasures. Tarafdar et al. (2011), for example, identifies three technostress inhibitors, namely literacy facilitation, technical support provision, and involvement facilitation. Also, as is summarized in Table 1, a number of variables have been identified that alter the influence of ICT on human stress perceptions. Future research, therefore, could investigate research questions such as the following:

14. *What are the biological effects of different technostress countermeasures?*

15. *To what extent are these possible effects influenced by moderator variables such as user experience?*

Concluding Comments

The IS discipline is an academic field that is deeply rooted in behavioral research. In addition to actual behavior toward ICT, behavioral intentions, attitudes, and beliefs are typically major construct categories in IS research (e.g., technology acceptance research). Hence, the measurement of constructs is often based on surveys (see a recent meta-study on this topic by Riedl & Rückel, 2011).

Against the background of this tradition in behavioral research and survey measurement, it is of particular concern that convincing arguments regarding the value that biology adds to a specific research topic are provided, and that these arguments are based on theoretical considerations and empirical evidence. The specific topic of interest proposed in this article is technostress. Importantly, many essential arguments on the value of neurobiological approaches for IS research have already been articulated in the literature (e.g., Dimoka et al., 2011, 2012; Riedl et al., 2010a, 2010b, 2012; vom Brocke et al., 2013). Foremost, it has been argued that neurobiology constitutes an important reference discipline for the IS field because the *complementary* use of biological concepts, theories, methods, tools, and data makes possible a better theoretical understanding of IS phenomena such as technostress.

In this context, Camerer et al. (2005) have made an informative statement on the introduction of novel approaches in a scientific discipline; specifically, they have commented on the increased use of neuroscience methods in economics: “Scientific technologies are not just tools scientists use to explore areas of interest. New tools also *define* new scientific fields and erase old boundaries. The telescope created astronomy by elevating the science from pure cosmological speculation. The microscope made possible similar advances in biology. The same is true of economics. Its boundaries have been constantly reshaped by tools such as mathematical, econometric, and simulation methods. Likewise, the current surge of interest in neuroscience by psychologists emerged largely from new methods, and the methods may productively blur the boundaries of economics and psychology” (pp. 11-12, italics in original).

Considering this statement, it may be argued that the increased use of neurobiological approaches will also define a new stream of research in the IS discipline, one that is designed to complement the existing streams, signifying the increasing maturity of the field.

I believe that biology offers a valuable knowledge base for the investigation of IS phenomena, as demonstrated in the present article, which is based on the example of technostress. If technology is the users’ foe, corresponding stress perceptions can be objectively measured. However, making technology the users’ friend must be a major goal of IS research. Whether or not a specific technology is user-friendly can also be investigated by means of biological approaches. This is an issue of real consequence, as signified by a recent study (Mauri et al., 2011) that uses biology to explain the success of Facebook, a technology that has recently reached one billion active users (www.facebook.com). Given the critical value of research into the biology of human interaction with technology, future studies can be expected to reveal rewarding insights.

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About the Author

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Appendix

This appendix describes the methodology used to identify the papers that are discussed in this article. Moreover, this outlines the search for technostress literature that pertains to the behavioral level of analysis. Altogether, the search process, as well as corresponding analyses, revealed that technostress research is highly fragmented across various scientific disciplines.

A search via *Google Scholar* (terms: technostress, condition: TITLE, date: 3-22-2012) resulted in 187 hits. A descriptive analysis of the Top-40 hits from this list (works ≥ 5 citations) shows, among other facets, that (a) there is an increasing number of corresponding publications across the past three decades (when controlling for a higher citation probability of older works), (b) library science, general psychology, and IS are the disciplines making the largest contributions to technostress research; library science has been the most significant contributor in terms of the number of works during the past three decades, while the topic has only started to gain notable momentum in IS outlets in the past single decade, (c) the thematic foci range from more practitioner-oriented topics (e.g., general and terminological descriptions, as well as management and coping) to more scientific issues (e.g., measurement, causes, effects, moderators), and in terms of quantity the former category dominates the latter, and (d) all empirical works, in addition to the papers that are based on pure anecdotal evidence, investigate the topic by means of self-reported data (i.e., interview and survey). The analysis is presented in the table on the next page.

This analysis enables the following conclusions: (a) technostress is a topic that holds increasing importance, (b) it is a phenomenon that is relevant across the boundaries of scientific disciplines, thereby being a notably interdisciplinary topic, (c) there is a need for more theoretical research, and (d) research studies published under the label of technostress are methodologically biased toward techniques from the social sciences (i.e., self-reports), whereas other approaches, particularly biological ones, are not used at all. Further analyses in *Web of Science*[SM] (term: technostress, condition: TITLE, date: 3-25-2012) resulted in 35 hits. Importantly, this additional investigation confirmed the *impression* of the non-existence of biological investigations into technostress.[26]

The finding regarding the deficit of biological investigations addressing technostress was astonishing, as stress is an inherently biological phenomenon that has a number of physiological effects—a fact that is even reflected in journal names such as *Stress: The International Journal on the Biology of Stress*. Thus, it appeared somehow strange that no article applied a biological research approach. An extension of the *Google Scholar* analysis to all 187 hits did *not* change this conclusion. Rather, only one article that was in press during the preparation of this manuscript has applied a neurobiological approach (Riedl et al., 2012).

Against the background of this finding, an extended search was performed in *Web of Science*[SM] (date: 3-25-2012). Rather than searching for the term "technostress," a concept that is obviously established only in non-biological technostress research, the ICT-related terms <computer, Internet, phone, e-mail, technology, visual> (condition: TITLE) were logically connected via <AND> to the stress-related terms <cortisol, adrenaline, noradrenaline, HPA, heart, blood pressure, skin conductance> (condition: TOPIC), as well as via an additional <AND> to the overall topic, namely <stress> (condition: TOPIC).[27]

The articles that this search has yielded, along with relevant sources found in the references of these papers (plus other references that were identified via other channels such as personal communication with colleagues), has led to a revision of the original conclusion. This altered search strategy revealed a notable number of peer-reviewed journal articles dealing with the phenomenon of technostress from a biological perspective. The identified papers are the ones discussed in this article.

[26] An article by Brod (1982) was identified as the oldest work explicitly using the term "technostress." Hence, the year 1982 may be viewed as the beginning of the history of technostress research.

[27] The term "visual" was used to identify articles dealing with visual display units (VDU) and visual display terminals (VDT).

Table Appendix. Google Scholar Analysis

Google Scholar (3-22-2012)		Year of Publication				Discipline				Thematic Focus							Type of Publication	
First Author, Year of Publication	Citations	80s	90s	00s	≥ 10	IS	PSY	LIB	MI	DES	MA/CO	HE/CO	MEA	CAU	EFF	MOD	Journal, Magazine	Book, Other
Brod (1984)	346	•					•			•								•
Weil (1997)	124		•				•			•								•
Kupersmith (1992)	50		•					•		•							•	
Brod (1982)	47	•							•		•						•	
Elder (1987)	47	•							•							•	•	
Tarafdar (2007)	43			•		•									•		•	
Hudiburg (1989)	41	•					•						•				•	
Ragu-Nathan (2008)	32			•		•							•		•		•	
Bichteler (1987)	25	•						•			•			•	•		•	
Brillhart (2004)	25			•					•		•						•	
Champion (1988)	22	•						•		•							•	
Tu (2005)	22			•		•										•	•	
Ennis (2005)	19			•				•		•							•	
Moreland (1993)	18		•						•							•	•	
Wang (2008)	16			•		•										•	•	
Bartlett (1995)	15		•					•		•							•	
Rosen (1997)	15		•				•			•								•
Gorman (2001)	15			•				•		•							•	
Rose (1998)	13		•					•					•				•	
Harper (2000)	13			•				•		•								•
Fisher (1999)	9		•						•		•						•	
Kupersmith (1998)	9		•					•		•								•
Sami (2006)	9			•				•							•		•	
Brod (1985)	8	•					•				•							•
McDonald (1983)	7	•							•		•							•
Sethi (1987)	7	•							•	•								•
Rosen (1998)	7		•				•			•								•
Hickey (1992)	7		•					•			•						•	
Fleet (2003)	7			•				•		•								•
Quinn (2001)	7			•				•			•						•	
Kasuga (1997)	6		•						•			•					•	
McPartlin (1990)	6		•						•			•						•
Shepherd (2004)	6			•					•							•		•
Tarafdar (2011)	6				•	•					•		•	•	•	•	•	
Tarafdar (2010)	6				•	•									•		•	
Caro (1985)	5	•							•		•						•	
Anderson (1985)	5	•							•							•	•	
Davis-Millis (1998)	5		•						•	•								•
Pitkin (1997)	5		•					•		•								•
Kupersmith (2003)	5			•				•		•								•
Top-40	**≥ 5**	**11**	**14**	**13**	**2**	**6**	**6**	**15**	**13**	**16**	**10**	**2**	**4**	**2**	**6**	**7**	**25**	**15**

Notes: This table shows a *Google Scholar* Analysis (terms: technostress, condition: TITLE, date: 3-22-2012). Total number of hits was 187. Works ≥ 5 citations are presented in the table (Top-40). Classification of works was performed by the author of this article based on title and abstract information. Discipline: IS: Information Systems, PSY: Psychology (general), LIB: Library Science, MI: Miscellaneous (e.g., management science). Thematic Focus: DES: Descriptive (e.g., terminology), MA/CO: Management/Coping, HE/CO: Health/Costs, MEA: Measurement, CAU: Causes, EFF: Effects, MOD: Moderators. Type of Publication: Other (e.g., proceedings publication).