System Response Time as a Stressor in a Digital World: Literature Review and Theoretical Model

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Abstract. The time delay between a user's initiation of a command on a digital device (e.g., desktop computer, tablet, smartphone) and the system's task completion, including the display of the result on the screen, is referred to as system response time (SRT). This specific system property has been the object of study since the 1960s, predominantly in the field of human-computer interaction. In most usage scenarios, SRT ranges from milliseconds to several minutes, and SRT is a function of various factors, including technical system capabilities such as processing power. One would assume that technological progress has reduced the relevance of investigations into the physiological and stress-inducing effects of long and/or variable SRT. However, as a result of the ever increasing complexity of information systems and digital devices, SRT is still a significant stressor in today's society. One could even argue that, due to the ubiquity of digital devices in almost every corner of life and the resulting frequent human-computer interactions, the relevance of SRT as a topic in scientific research and practice has even increased in the last years. Against this background, the present article conceptualizes SRT as a stressor in a digital world, reviews major research results, and, based on that review, develops a theoretical model. This model is intended to guide future research on SRT.

Keywords: Digital stress · NeuroIS · Response time · Stress · Technostress

1 Introduction

The time delay between a user's initiation of a command on a digital device and the system's task completion, including the display of the result on the screen, is referred to as system response time, hereafter SRT. This specific system property has been the object of study since the 1960s (e.g., [1, 2]), predominantly in the field of human-computer interaction (HCI). SRT typically ranges from milliseconds to several minutes. Moreover, SRT depends on numerous factors, such as the complexity of the task or processing power of the system [3]. Importantly, evidence indicates that long and/or variable SRT may increase stress in users of digital devices [4].

One would assume that technological progress has diminished the relevance of investigations into the physiological and stress-inducing effects of long and/or variable

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SRT. However, due to the ever increasing complexity of information and communication technology, SRT is still a significant stressor in today's society (e.g., [5]). One could even argue that in a highly digitalized world, the relevance of SRT as a topic in scientific research and practice has even increased in comparison with previous epochs. Considering the relevance of SRT for users' stress and well-being, along with the impact of SRT on other important outcome variables in HCI (e.g., user satisfaction, technology acceptance, performance, or productivity), the present article conceptualizes SRT as a stressor in a digital world and reviews major research results which have shown that long and/or variable SRT may lead to notable physiological stress reactions. Based on that review, we develop a theoretical model which is intended to guide future research on SRT. Ultimately, it is hoped that the insight which can be developed based on this model and corresponding empirical investigations help to mitigate, or even eliminate, the negative physiological consequences of long and/or variable SRT. In other words, it is hoped that the theoretical foundation developed in this paper helps to develop effective interventions in practice.

2 Method

Riedl [6] indicates that "[d]irect 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" (p. 18). Based on a comprehensive review of academic literature which has been published since the 1970s, Riedl [6] identified a number of negative biological effects that may emerge from human interaction with information and communication technology (ICT). Importantly, this review also identified long and/or variable SRT as major stressor. In a more recent paper on the potential of blood pressure measurement for technostress research, Fischer et al. [7] also identified research on SRT as one of the most important fields where neurophysiological devices are used in the context of technostress. Based on these findings, in the current paper we a look into selected technostress studies which report on the physiological and stress-inducing effects of SRT.

Drawing upon 12 papers on SRT that were included in these reviews (i.e., 10 empirical papers [8–17] and 2 review papers [3, 4]), we conducted a forward search in Google Scholar on 12/22/2017 and 12/23/2017 in order to identify more recent empirical research (the most recent empirical paper included in these reviews was by Trimmel et al. [16] from 2003). This procedure led to a total of 678 hits, of which 7 were empirical papers that dealt with SRT using neurophysiological measures. Hence, we ended up with a sample of 19 papers, which we analyzed in detail. The results of this analysis are presented below.

3 Results of Reviewed Studies

In Table 1, we offer an overview of the empirical studies that are part of our review, including the main characteristics of the sample, the SRT conditions, and the effects on individual physiology.

In a two-stage case study, Johansson and Aronsson [11] measured by means of multi-item survey instruments, in the first stage, stressors (e.g., rush) and symptoms (e.g., irritation) related to computer work. In the second stage of the study, users with extensive computer work and users with a low degree of computer work were investigated in detail. In essence, this study found notable degrees of technostress (based on self-report instruments and biological measures). Importantly, the authors concluded that “stress and strain in computerized work may be counteracted … by reducing the duration and frequency of breakdowns [and] by reducing response times in the system” (p. 159). Thus, research already indicated more than three decades ago that stress resulting from long SRT constitutes a significant issue.

Trimmel et al. [16] experimentally investigated SRT, and the authors argued that long SRT causes uncertainty, which, in turn leads to arousal and stress. Twenty-five students participated in the study, 14 skilled and 11 unskilled Internet users (age range: 20–30 years). The task was to answer questions, based on an online information search (e.g., booking a hotel). SRT was manipulated as independent variable: short (2 s), medium (10 s), and long (22 s). Heart rate and skin conductance were used as dependent variables and investigated at three periods: the 10th to 5th second before the waiting time (baseline), during waiting (2, 10, or 22 s), and the 5th to 10th second after waiting (post-baseline). Also, mental load was measured based on a 163-mm analog scale.

The study revealed significant physiological stress responses. Longer SRT led to increased heart rates and enhanced electrodermal activity (note that no significant differences were found between the baseline and post-baseline conditions). Moreover, results indicate that increased activity of the physiological signals were independent of expertise, suggesting that no long-term habituation to long SRT takes place. Furthermore, in post-hoc analyses, the sample was split into two groups: low and high mental load. It was found that individuals experiencing high mental load do have a higher overall heart rate. Specifically, a heart rate of 114 beats per minute was observed for the 22-s condition. Considering that the heart rate of healthy humans is between 60–100 beats per minute at rest [25–27], such an increase is significant.

Interpreting their findings, Trimmel et al. surmise that the elevation of heartbeat and skin conductance may reflect increased attention, as well as active mental performance, because the participants might have given thought to potential reasons for delayed response times. In their recommendation for practice, the authors write that “short SRTs 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).

In a seminal research program, Boucsein and colleagues studied the effects of the length and variability of SRT on physiological signals. In essence, long SRT (though what is considered long is task-dependent) and/or a high degree of variability in SRT

Table 1. Overview of empirical SRT studies using neurophysiological measures

Study	SRT conditions	Effects
Johansson and Aronsson [11] Sweden, 21f	–	Mainly anecdotal
Kuhmann et al. [17] Germany, students, 22f/46 m	Short: 2 s Long: 8 s 7 steps of variability	Longer SRT: higher systolic BP, more spontaneous SCR, higher SCL No effect of SRT variability
Kuhmann [13] Germany, students, 10f/38 m	SRT: 2 s; 4 s; 6 s; 8 s	No effect of SRT
Schleifer and Okogbaa [14] USA, typists, 45f	Short: .35 s Long: 3-10 s	No effect of SRT
Schaefer [18] Germany, students, 10f/38 m	SRT: 2 s; 4 s; 6 s; 8 s	No effect of SRT
Emurian [8] USA, students, 11 m	Constant: 8 s Variable: 1–30 s	No effect of SRT variability
Emurian [9] USA, students, 16f/16 m	Short: 1 s Long: 10 s	Shorter SRT: higher systolic BP
Harada et al. [10] Japan, students, 6f/6 m	Short: < .1 s Long: .3-7 s	Shorter SRT: higher diastolic BP, lower HR
Thum et al. [15] Germany, students, 20f/20 m	Short: .5 s Medium: 1.5 s Long: 4.5 s	Longer SRT: higher HRV (mean square of successive differences), higher SCR (nonspecific electrodermal responses), lower systolic BP, lower diastolic BP, lower respiration rate, lower facial EMG activity
Kohlisch and Kuhmann [12] Germany, students, 15f/27 m	Short: 1 s Medium: 5 s Long: 9 s	Shorter SRT: higher mean BP, more frequent non-specific SCR
Trimmel et al. [16] Austria, students, 14f/12 m	Short: 2 s Medium: 10 s Long: 22 s	Longer SRT: higher HR Shorter SRT: more non-specific SCR SRT (general): higher SCL

(*continued*)

Table 1. (*continued*)

Study	SRT conditions	Effects
Kohrs et al. [21] Germany, 9f/8 m	Short: 0 s Long: .5 s Omitted feedback	more pronouned activation in putamen in response to delayed feedback (vs ommitted feedback)
Kohrs et al. [19] Germany, 16f	Short: .5 s Medium: 1 s Long: 2 s	Longer SRT: more non-specific SCR, lower HR
Taylor et al. [20] USA, 13f/11 m	SRT: 0; .025 s; .050 s; .1 s; .2 s; .4 s	No individual effects reported, only performance of prediction model for individual frustration levels
Yang and Dorneich [22] USA, students, 7f/14 m	Short: 0 s Long: 2 s or 3 s	Longer SRT: anger (Facereader), increased electro-dermal activity
Kohrs et al. [23] Germany, 10f/11 m	Unexpected, infrequent delays: Short: 2 s Medium: 4 s Long: 6 s	Longer SRT: left and right anterior insular cortex, posterior medial frontal cortex, left inferior parietal lobule, right inferior frontal junction and default network, medial prefrontal and posterior cingulate cortex
Kohrs et al. [23] Germany, 7f/12 m	Frequent delays: Short: 0 s Long: .5 s (.3-7 s)	No differences in brain activations
Kohrs et al. [23] Germany, 9f/8 m	Frequent delays: Short: 0 s Long: .5 s (.3-7 s) & Omissions of Feeback	Longer SRT: bilateral anterior insula, posterior medial frontal cortex, and left inferior parietal lobule
Yang and Dorneich [24] USA, students, 7f/14 m	Short: 0 s Long: 2 s or 3 s	Longer SRT: anger (Facereader)

BP = blood pressure; EMG = electromyography; HR = heart rate; HRV = heart rate variability; SCL = skin conductance level; SCR = skin conductance response; s = seconds

may result in considerable physiological stress reactions, such as skin conductance elevation (e.g., [17]). Boucsein and colleagues conducted several laboratory experiments on the physiological effects of SRT length. Table 2 summarizes the findings of this research group with respect to SRT length [4].

Table 2. Summary of research findings on SRT and time pressure (source: Boucsein [4])

Short SRT (0.5–2 s) with time pressure
Systolic and diastolic blood pressure increases
Heart rate variability decreases
Respiration rate increases
Muscle tension on the forehead increases
Frequency of nonspecific electrodermal responses increases
Short SRT (0.5–2 s) without time pressure
Systolic and diastolic blood pressure increases
Heart rate increases
Long SRT (8 s or longer) with time pressure
Skin conductance level increases
Frequency of nonspecific electrodermal responses increases
Amplitude of nonspecific electrodermal responses increases
Systolic and diastolic blood pressure decreases
Respiration rate decreases
Long SRT (8 s or longer) without time pressure
Amount of electrodermal activity increases
Frequency of nonspecific electrodermal responses initially increases and later decreases

In two studies, Yang and Dorneich [22, 24] investigated the effects of varying system delays on the interaction of individuals with robots. Twenty-one students were instructed to operate a robot through a simple or more difficult maze while their inputs were implemented with or without a time delay. In the trials reported in the earlier study, they found significant differences in arousal based on task difficulty (higher task difficulty led to more arousal reflected in electro-dermal activity) and SRT (longer SRT led to more arousal reflected in electro-dermal activity), as well as a significant interaction of both (i.e., high task difficulty and long SRT together led to the highest physiological arousal). However, Yang and Dorneich were not able to replicate these findings in the more recent study.

Against the background of these findings, it can be concluded that long SRT may significantly activate the sympathetic part of the autonomic nervous system (ANS). The ANS consists of two parts: sympathetic and parasympathetic. While the former is responsible for implementation of a “fight-or-flight” (stress) response, the latter is the underlying structure of a “rest-and-digest” (relax) response. It follows that the sympathetic division is stimulatory, while the parasympathetic division is inhibitory. In stressful situations, the sympathetic part of the ANS becomes active and stimulates a number of responses, such as (Riedl and Léger [28], p. 41): pupil dilation (i.e., elevated attention), skin conductance increase (i.e., higher arousal), airway relaxation, heartbeat acceleration, intense glucose release, and muscle tension.

Moreover, recent research also shows that certain parts of the central nervous system (CNS), specifically parts of the brain, may become activated by varying SRT. Kohrs et al. [21, 23] report on laboratory experiments which utilized fMRI (functional magnetic resonance imaging) to investigate the brain regions that are activated during different SRT conditions. The task of their participants was to categorize tones, depending on their modulation (upward or downward). Response times were varied for the feedback participants received when entering their answer. In their first experiment, the delays were infrequent and therefore unexpected. In the case of delayed feedback, a number of brain areas were more profoundly activated (e.g., the left and right anterior insular cortex (aI), the posterior medial frontal cortex (pMFC), the left inferior parietal lobule (LPI), and the right inferior frontal junction (IFJ)), including the medial prefrontal and posterior cingulate cortex, which are involved in the attentional control of individuals, indicating that individuals did not focus on the task any longer, when delays lasted too long. This effect disappeared in their second experiment though, when delays occurred frequently and individuals therefore managed to adapt to them. In their third and last variation, they kept the delays frequent, but also included omissions of feedback, which basically mimicked a short breakdown of the system. In this case, the initial activations of the first experiment were prevalent again, particularly when delays occurred after an omission event, this is likely to be because participants expected further "breakdowns" and thus are not able to trust the system any longer. Consequently, the authors recommend that breakdowns should be avoided at any cost and that delays, if still present and above a noticeable threshold (.2 s), should at least be kept consistent so that users can adapt to them. This recommendation can also be supported by evidence involving the autonomic nervous system, which clearly indicates profound stress reactions in response to perceived system breakdowns (e.g., [29, 30].

4 Theoretical Model

Previous research has revealed interesting findings on the impact of length and variability of SRT on individual physiology. Yet, as can be seen in Table 1, there are still some inconclusive results that warrant further investigation. For example, while Kuhmann et al. [17] report lower levels of systolic blood pressure during conditions with short SRT, Emurian [9] reports the exact opposite finding. In addition, in some studies that utilized blood pressure measurements, diastolic blood pressure changed during different SRT conditions [10, 12, 15], but not always in conjunction with systolic blood pressure [9, 10, 17]. The same holds true for heart rate measurements (Trimmel et al. [16] report higher heart rates during conditions of long SRT, while Kohrs et al. [19] report the exact opposite) and electro-dermal activity, where some studies report more electro-dermal activity due to long SRT [15, 22], while others report more electro-dermal activity due to short SRT [12, 19].

An early indication for the potential reasons behind such different findings was given by Kuhmann [13] who had also investigated the effect of SRT length (2 s, 4 s, 6 s, 8 s). In conclusion, having not found any significant effects, he hypothesized that this might be due to a lack of time pressure that study participants felt during the laboratory experiment. This finding draws attention to the importance of moderators in the context of SRT.

In his review of previous work on SRT, Boucsein [4] also reports on important moderators of the relationship between length and/or variability of SRT and ANS activity. Specifically, he outlines the following major moderators: user experience, SRT expectations of a user, task (e.g., data entry versus complex decision making with a computer), and context factors (e.g., time pressure).

Variables that are part of one of these three categories (user, task, or context) have also been investigated in our reviewed studies. Regarding *user characteristics*, Emurian [9] found that gender had an important impact on physiological measures, with men having an overall higher blood pressure, while women had a higher heart rate, independent of the SRT condition. Regarding SRT, women showed particular masseter activity (indicative of annoyance) during short SRT conditions. Based on structured interviews, it was also investigated whether personality characteristics (Type A/B) could have an impact on physiological changes in response to different SRT conditions. Yet, this categorization was done post-hoc and only used to hypothesize that personality characteristics might also have an impact on the perception of SRT. Also, expectations of SRT can be of importance, with Johansson and Aronsson [11] reporting that study participants would accept a delay of up to 5 s, but only a small fraction would be willing to accept a delay of more than 10 s, independent of the task or system.

Regarding *task characteristics*, Johansson and Aronsson [11] reported that they were surprised that it was not the group of customer service employees who reported most problems due to computer misbehavior, but the group of individuals who spent their day feeding in data. This could, presumably, point to the dependence on technology used or monotony of computer-related tasks as potential moderators. Such an assumption regarding task monotony was also made in other studies [12, 14, 15] and was confirmed in a study by Schleifer and Okogbaa [14] who found that more monotonous tasks led to lower heart rates and higher heart rate variability, this is likely to be because study participants did not put as much effort into the completion of a task as in the beginning of the study (i.e., mental fatigue). In addition, Yang and Dorneich [22] also showed an interaction effect for task difficulty and SRT, with physiological arousal being highest when tasks are difficult and SRT is long.

Finally, we also need to pay attention to *characteristics of the context* of a study when investigating the effects of SRT. A number of studies included incentives that were connected to the performance of an individual (e.g., monetary), which put additional pressure on them to complete a task in time [8, 9, 12, 14, 15]. In the case of Schleifer and Okogbaa [14], incentivized pay (i.e., better pay for better task performance), led to reduced heart rate variability and increased overall blood pressure, which are indicators of stress. A factor that is often included in studies on SRT as well, but has, for example, been lacking in the study by Kuhmann [13], is the time pressure that is prevalent in almost every work context today [10, 17]. The effect that the presence or absence of such a moderator can have in the study of SRT is illustrated in the review by Boucsein [4]. He summarized the effects that short and long SRT had in the presence or absence of time pressure in previous studies that his research group had conducted (see Table 2).

Based on the evidence discussed in this paper, we developed a theoretical model, which is shown in Fig. 1. In essence, the model conceptualizes SRT as independent variable, with the properties length and variability. The dependent variable in the model is autonomic nervous system (ANS) activity, with five important ANS parameters (blood pressure, heart rate, respiration, skin conductance, muscle tension). Moreover, the model conceptualizes three categories of moderators: user characteristics (e.g., SRT expectation), task characteristics (monotony of the HCI task), and context factors (e.g., time pressure to complete a HCI task).

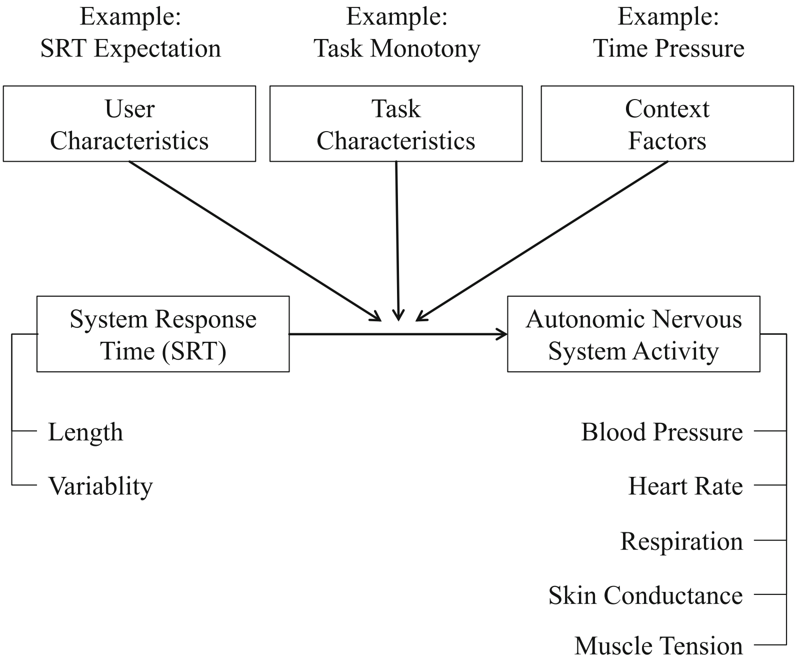

Fig. 1. Theoretical model on the stress-inducing effect of system response time (SRT)

We focus particularly on ANS activity, because related tools have also become accessible to researchers outside of neuroscience and psychology, particularly in Information Systems (IS) research, HCI, and software engineering [31, 32]. Tools such as chest belts to measure heart rate or self-measurement devices to collect blood pressure values could be used by software developers to improve SRT with regard to individual stress levels, thereby improving individual well-being, performance, and productivity. In contrast, brain measurement tools are more difficult to apply in natural settings and their application could be perceived as too resource-intensive in development projects [33]. However, it will be rewarding to see what insight future research and development projects will reveal with regard to the application potential of both self-measurement devices and brain measurement tools in software engineering.

5 Conclusion

In this paper, we have outlined the link between SRT conditions and physiological responses, mainly related to the autonomic nervous system. Based on a review of the literature, we found that there are inconclusive findings regarding the impact of the length and variability of SRT on individual stress. Therefore, we proposed a theoretical model, which includes user, task, and context characteristics as important moderators of the relationship between SRT and physiological responses. A call for future research is made to systematically study the hypothesized relationships in this model. With this call for research focusing on moderating variables, we are also following recent findings from HCI research. For example, Attig et al. [34] reviewed system latency guidelines and concluded that “latency thresholds are not cast in stone, yet, are system-, task- and person-dependent” (p. 10).

Research based on our theoretical model should bring us closer to what Boucsein [4] has dubbed the “optimal response time” for a given task based on biological, performance, and health measures. He indicates that the”optimum” is reached in a situation with the following characteristics:

- no marked increases in cardiovascular activity,
- low frequency of nonspecific electro-dermal responses,
- no increased general muscle tension,
- low reports of pain symptoms, and
- good performance in the HCI task.

A NeuroIS approach is recommended to conduct the empirical studies (a comprehensive description of the NeuroIS approach is available in Riedl and Léger [28]).

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