"Time is Bandwidth"? Narrowing the Gap between Subjective Time Perception and Quality of Experience

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***Abstract*—Over the last couple of years, the scope of Quality of Experience (QoE) research has been constantly extended, most recently to the field of Web QoE in the context of HTTP-based applications. In this paper, we address the question whether it is sufficient to reduce typical Web QoE assessment scenarios to the temporal aspects of waiting for task completion, which would allow to attribute the resulting logarithmic laws to well-known psychological insights on human time perception. We demonstrate that while this attribution is valid for simple waiting tasks which are typical for simple data services like e.g. file downloads, the case of interactive web browsing is much more complex. We show that this is not only because technical issues prevent bandwidth and download time from being directly correlated with each other in a simple manner, but also because user perceived web page load times strongly deviate from technical page load times. Consequently, existing approaches towards assessment and modeling of web browsing QoE have to be critically reviewed and redesigned.**

***Index Terms*—Quality of Experience, Quality of Service, Psychophysics, Weber-Fechner Law, interactive Data Services**

I. Introduction

Quality-of-Experience (QoE) currently receives a strongly growing attention from both academia and industry, because it constitutes a new framework for describing the qualitative performance of communication systems and applications. Going far beyond established Quality-of-Service (QoS) concepts, QoE tries to link performance as closely as possible to the subjective perception of the end user. This shift towards user centricity rather than technology centricity is motivated by the fact that users nowadays may choose from a broad range of technological and commercial options for satisfying their communication and entertainment needs, which results in intensified competition between network providers together with decreasing prices, respectively. Hence, the users find themselves in an empowered position allowing them to choose the provider best fulfilling their needs. Assuming that tariff schemes may be of highest user priority concerning the decision for a network provider, their second decision criterion is likely to be the expected and experienced quality of the service.

On the other hand, network providers have to face a steady increase of network traffic volumes they have to cope with. They need to trade off between network investments to secure user experienced quality of the network and economical constraints in order to remain price competitive. This problem becomes particularly eminent in the context of interactive web applications and file downloads, where high latency and long waiting times caused by low quality network access directly translate into user annoyance and churn.In order to answer the question: Which network quality (QoS) is sufficient to ensure a certain degree of user satisfaction? QoE sets out to map underlying technical network conditions (including QoS conditions of the network) to high-level end-user quality perception. Recent work on this matter [1], [2] sets out to identify natural psychophysical relationships between the network (stimulus) and user perception (response), with network-induced waiting time being a specific example of such a stimulus which directly affect user satisfaction and thus QoE.

Indeed, user quality perception in the context of interactive data services is determined by such waiting times to a large extent [3], [4], a fact which has led to the catchy notion of WWW as *World Wide Wait* [5]. A large share of services e.g. file downloads, E-Mail browsing, picture viewing or basic web browsing is characterized by an information request from user side and respective waiting times until the request is fulfilled. The past shift from UDP media streaming to TCP media streaming (e.g. youtube.com) has extended the relevance of waiting times also to the domain of online video services. Hence within this paper we try to answer the following question:

Which waiting times are sufficient to ensure a certain degree of user satisfaction?

The remainder of this paper is structured as follows: in section II we discuss the relation between psychophysics, quality of experience and human time perception in particular. Section III describes a set of studies which have been conducted in order to prove that for simple interactive data services, time perception principles from psychology are also applicable to explaining the logarithmic relationship between waiting times and resulting user satisfaction ratings. In section IV we investigate whether the same relationship also holds true for more complex services such as web browsing. By doing so, we identify several difficulties on the technical as well as the user level which increase the complexity of quantifying web browsing QoE considerable. Finally, section V concludes the paper with a brief summary and outlook.

II. Psychophysic perspective and related work on human time perception

Studying the fundamental underlying laws for Quality of Experience recently has become a topic of increasing interest in the scientific community, see for instance [6], [7] and references therein. In this context, the application of stimulus-response models for QoE measurement scenarios has turned out to allow important insight into the relationship between (technical) QoS and (subjective) QoE metrics. We believe that especially the logarithmic form of the well-known Weber-Fechner Law (WFL) [8], which in a sense has earmarked the birth of psychophysics as a scientific discipline of its own, is of pivotal relevance here.

Essentially, the WFL traces the perceptive abilities of the human sensory system back to the perception of so-called "'just noticeable differences"' between two levels of a certain stimulus. For most human senses (vision, hearing, tasting, smelling, touching, and even numerical cognition, such a just noticeable difference can be shown to be a constant fraction of the original stimulus size. For instance with touching, experiments show that we are able to detect an increase in the weight of an object in our hands if this is increased by around 3%, independently of its absolute value. As a straightforward conclusion, the resulting mathematical interrelation is of a logarithmic form and can be used to describe the dependency between stimulus and response/perception over several orders of magnitude.

In [1], we have demonstrated first evidence concerning the applicability of the WFL also in typical QoE contexts, with VoIP and mobile broadband as key trial scenarios. For the present work, especially the experiments on file download are relevant, where users are essentially asked to perform waiting tasks (clicking on a link in order to start the download of a mp3 or zip file, and attending the completion of the download) for different downlink bandwidths. From this test setup, one could easily argue that, based on the indirect dependency of waiting time on offered bandwidth, in fact we have measured the user's perception on plain waiting time which turns out to be of logarithmic form. In this sense, the main conclusion of [1] could indeed be expressed "time is bandwidth". A more detailed analysis of the test results shows that reality is much more intricate than expected. This issue has motivated the research reported this paper including the subsequent in-depth survey on the psychology of human time perception.

Work on human time perception covers a wide range of temporal perspectives on human behavior (see [9] for a comprehensive review), therefore we focus on contributions dedicated to the relationships between human time perception and psychophysical principles. Initial work in this field has been conducted by [10] already in 1975, where a relationship between the magnitude of the error of time estimations and the duration of the sample length to be estimated has been identified and attributed to Steven's Power Law [11]. Successive work by [12] extended these results and added other models including the WFL, while [13], [14] set out to identify the minimal achievable error for time estimation based on the aforementioned models. The authors came to the conclusion that the relationship between estimation error and stimuli length is constant, which is essentially a version of Weber's law where the estimation error (termed 'Weber Fraction') is equivalent to the just noticeable difference already discussed above. Extension of these results to time related problems in other disciplines such as medicine [15] or consumer behavior research [16], [17] has proven that these relations can be successfully transferred from psychological lab studies to real world problems. Of particular interest to our problem is the work of [16], which shows that for the subjective evaluation of waiting times on a linear scale a logarithmic relationship as described by the WFL does apply.

In the context of interactive data services a number of studies and guidelines exist: [18] defines maximum waiting times for interactive data services unfortunately without empirical evidence how violations of these guidelines do impact user perception. [19] gives similar recommendations about which waiting times are acceptable to the perceived interactivity of interactive data services. However these recommendations do not differentiate between different kinds of such services. Studies conducted by [3], [20] evaluate user perception of waiting times but have not used ACR scales or evaluated only attitudes toward certain services rather than the user satisfaction with the service. Similar to the aforementioned consumer behavior studies, [21], [22] tried to quantify the influence of time fillers or design characteristics on the evaluation of waiting times. Especially interesting is the work of [23] who conducted studies of waiting times in interactive data services similar to the studies described in this paper. However, they only describe the correlation between waiting times and their evaluation without associating their results with fundamental underlying relationships of psychophysical perception.

III. Waiting Tasks in Interactive Data Services

In order to address the open issues on waiting time evaluation from related work, we formulate the following "WQL hypothesis" quantifying the interdependency between waiting time and QoE:

WQL: The relationship between **W**aiting time and its **Q**oE evaluation on a linear ACR scale is **L**ogarithmic.

We conducted a series of subjective user studies in order to validate the WQL hypothesis and to address open issues on waiting time evaluation. In particular, scenarios for interactive data services were selected in which users experience clearly defined waiting times. In order to validate the WQL hypothesis and to focus on waiting time QoE, the influence of other factors on the user perceived quality has to be minimized. Therefore, we consider simple[1] scenarios such as file downloading or setting up a wireless Internet connection via 3G. The conducted experiments are described in Section III-A. The results of our study in Section III-B and of a study from related work [23] in Section III-C clearly indicate that the WQL hypothesis cannot be rejected.

A. Subjective Study Description for Simple Tasks

When studying human time perception, due to the manifold of influencing factors, it is important to define precisely which kind of temporal phenomena one is going to apply and study. Therefore we have used the overview provided in [9] to define which characteristics of human time perception apply to our problem.

The subjects were asked to execute three simple tasks described in Table I. In the studies, the users were sitting in front of a laptop. A network emulator was customized in order to delay the task execution to certain preset execution times. After each of these tasks the users were prompted for their *Satisfaction with the performance of the connection* on a five point ACR scale compliant to [24]. These simple tasks were chosen with the particular attention to minimize possible distraction due to concurrent tasks [25]. Technical details of the studies can be found in [1], [26].

TABLE I: Subjects were asked to execute different tasks while the waiting time was manipulated.

Task description	*Abbrv.*
"Connect to the 3G network. You are connected when the dashboard button turns green and states *connected*"	CST
"Please download the given file"	DL
"Please go to the next picture / start a google search on ..."	PLT

B. Subjective Ratings and the WQL for Simple Tasks

Next, the results of the subjective user studies for the different tasks are presented and the WQL hypothesis is applied. Therefore, the results of the different experiments are illustrated in the following way. The mean opinion score (MOS), i.e. the average over the subjective ratings for the same test condition, is plotted depending on the preset waiting time t with some markers, while the logarithmic curve fitting $QoE(t)$ according to the WQL is plotted as solid or dashed line. For the fitting, we use a logarithmic function with two parameters a and b which are derived by minimizing the least square errors between the fitting function and the MOS values.

$$QoE(t) = a \cdot ln(t) + b \quad (1)$$

[1]simple in the sense of waiting time being the dominant QoE influence factor

First, the connection task 'CST' is considered. The users were asked to connect to a 3G network via the dashboard client (modem frontend software), while the test supervisor manipulated the connection setup time. As one can see in Figure 1, the relationship of the waiting time evaluation on the y-axes does coincide very well with the logarithmic fitting, yielding a coefficient of determination $D = 0.99$, i.e. close to perfect match of 1.

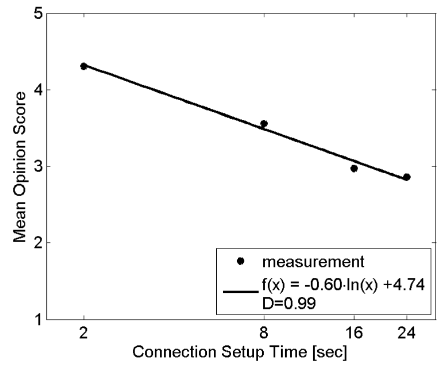

Fig. 1: Connection Setup Time for 3G access (CST task).

Figure 2 depicts the results of the file download tasks in which a 2.5 MB and a 10 MB file were downloaded by the users. The measurement studies were conducted in 2009 first and repeated in 2011. It can be seen that the file size influences the evaluation of the waiting time. The same waiting time results in significantly different MOS scores depending on the file size. For example, a waiting time of 38 s for the 2.5 MB files yield a MOS of 2.75 whereas the MOS of the 10 MB files was 3.58. This can be explained by the fact, that the expectation dimension of QoE (cf. [27]) interferes here. If people do know that the file size is large, they have different expectations regarding the respective download time to expect. As this expected time is longer in case of the 10MB files compared to the 2.5MB files, the ratings for the 10MB files are better. A further discussion on expectations and their influence on waiting time evaluation can be found in [16]. Another influence of altered expectations is visible between the ratings of the larger files. The rating slope of the more recent study from 2011 is steeper, which indicates that subjects in the recent study were expecting better performance from the network, hence lower waiting times. Details of the the logarithmic fitting and its goodness of fit in terms of coefficient of determination can be found in Table II.

TABLE II: DL task: Logarithmic fitting parameters and goodness of fit for download of files (see Figure 2).

file size	year	gof. D	logarithmic fitting function
2.5 MB	2009	0.98	$QoE(t) = -1.14\ln(t) + 6.83$
2.5 MB	2011	1.00	$QoE(t) = -1.12\ln(t) + 6.89$
10 MB	2009	0.98	$QoE(t) = -1.68\ln(t) + 9.61$
10 MB	2011	0.98	$QoE(t) = -1.68\ln(t) + 9.61$

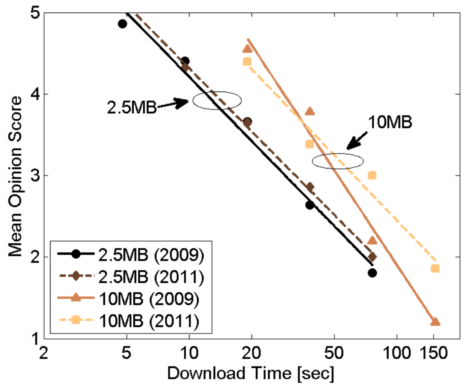

Fig. 2: Download of files of various sizes was investigated in two subjective user studies conducted in 2009 and in 2011, respectively (DL task).

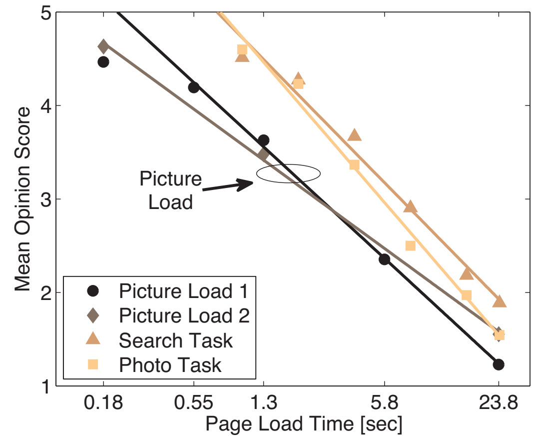

Fig. 3: User satisfaction for various constant page load times (PLT task).

Figure 3 shows the result for manipulated page load times (PLT task). The subjects were asked to browse through a picture album or to perform google searches. In both cases the request for the next picture and the search result were delayed for a certain time, respectively. The user study for the 'picture load' task was repeated twice. In addition, a 'photo' task has been conducted which differs from the 'picture load' task in the technical realization of the instrumented waiting time. For the 'picture load' (and the 'search') task, the HTTP requests were delayed, while for the 'photo' task the HTTP response instead of the HTTP request was delayed. However, this does not lead to observable differences from the end user's point of view. Since in the aforementioned examples the ratings do coincide with the logarithmic fitting pretty well – except for the lowest load time $t = 0.18\,\text{s}$ for the 'Photo task' in Figure 3. In that case, the root mean squared error (RMSE) is about $R = 0.2045$. We explain this by the fact, that the two shortest time settings (0.18 s and 0.44 s) are already so convenient, that for the lower value does not lead to a far better waiting time evaluation. This means that QoE reaches saturation for small waiting times and that the WQL hypothesis only applies above the saturation point, i.e. for noticeable waiting times. It has to be noted that this is in line with psychological time perception literature stating that waiting times below 0.5 s of waiting time have to be treated specially [9]. Therefore, the parameters of the logarithmic curve fitting are derived without considering user ratings for waiting times below 0.5 s. Then, the RMSE is about $R = 0.0446$. All logarithmic fittings and goodness of fit values are given in Table II.

TABLE III: PLT task: Logarithmic fitting parameters and goodness of fit for loading times of pages (see Figure 3).

task	gof. D	logarithmic fitting function
Picture Load 1	1.00	$QoE(t) = -0.80\ln(t) + 3.77$
Picture Load 2	1.00	$QoE(t) = -0.63\ln(t) + 3.58$
Search Task	0.98	$QoE(t) = -0.88\ln(t) + 4.72$
Picture Load Task	0.99	$QoE(t) = -1.00\ln(t) + 4.73$

C. Validation of WQL for Interactive Data Services

Figure 4 shows results from another study where waiting times were manipulated by [23]. In order to compare their results to the results we have obtained, we have also plotted the logarithmic fittings adhering to equation 1. It can be seen that also these results can be closely approximated by the shown logarithmic fitting, hence coinciding with the results from our studies.

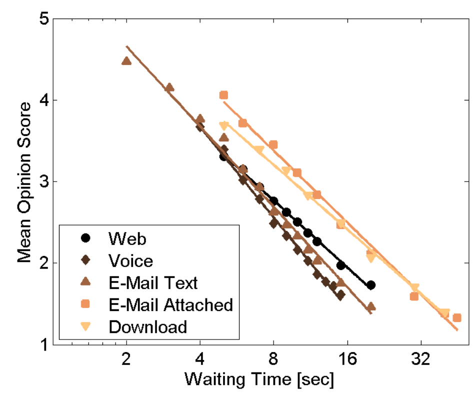

Fig. 4: Results from [23] supporting the WQL hypothesis, i.e. logarithmic relationship between MOS and waiting times, for several services.

Summarizing, we have shown that the relationship between waiting time evaluation on a linear ACR scale and its respective waiting time can be very well approximated via the proposed logarithmic function. Hence, the WQL hypothesis cannot be rejected.

IV. Challenges and Practical Issues for Web Browsing

In this section, we discuss challenges and practical issues concerning more complex scenarios such as browsing the web. The successful identification of the logarithmic relationship for the plain waiting tasks in Section III and the similar modeling approach for web browsing QoE of [28] encouraged us to test the WQL hypothesis for web browsing as well. Although the WQL hypothesis may also be valid for web browsing, i.e., the relationship between waiting time and web QoE is logarithmic, the measurement of waiting times for web pages is very challenging. First, bandwidth cannot be directly mapped to page load times or waiting times. Second, page load times are perceived different by human subjects than measured on application level.

In the following, the corresponding web QoE experiments and their results with respect to WQL are presented. We took data from a recent web browsing study where users were asked to browse five different webpages while we manipulated the downlink bandwidth and gathered respective ratings for each bandwidth setting (details can be found in [26]). We assumed that these bandwidths could be recalculated into waiting times if the number of objects and their size are known as recommended by [28]. To be able to do that a posteriori we gathered these properties through passive traffic monitoring which we were running in parallel throughout the test.

Figure 5 shows the measured MOS and the correspondong logarithmic fitting in dependence of the downlink bandwidth. However, it can be seen that the logarithmic fitting does not match the MOS values very well. We identified the following three major reasons for this:

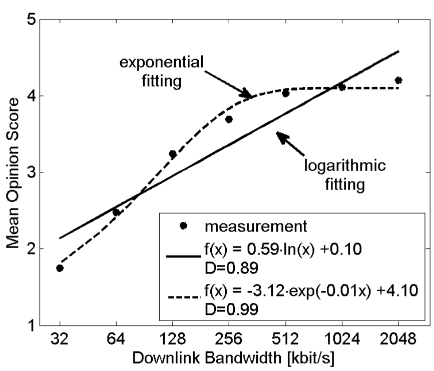

Fig. 5: Web browsing with downlink bandwidth limitation instead of instrumented constant page load times.

1. Stimuli vs. Impairment. First of all, the WQL hypothesis relates waiting times to QoE. Similar to the Weber-Fechner law, a stimulus, i.e. waiting time, is related to user perception. However, bandwidth is not a stimulus in a strict psychological sense. Hence, the WQL hypothesis can only be applied if there is a linear relationship between bandwidth and time. In contrast, the IQX hypothesis introduced in [29] proposes an exponential interdependency between QoE and QoS parameters like bandwidth. Figure 5 shows in addition the corresponding exponential curve fitting which obviously seems to be quite appropriate to describe web QoE with respect to bandwidth.

2. Time vs. Bandwidth. Since the logarithmic fitting does not perform well, the relation between waiting time and bandwidth is not linear. However, even the relation between objectively measurable page load time and bandwidth is not linear due to the complexity and interactions of the HTTP and TCP protocol with the network performance (e.g. impact of high bandwidth-delay product on TCP performance; impact of TCP's slow start, congestion and flow control on loading times of small pages; HTTP pipelining. cf. [30]). This leads to complex, non-linear models of *network-level page load times* for entire web pages. Furthermore, in addition to the network page load time, the local machine rendering and displaying the web page requires a certain amount of time. Hence, the *application-level page load time* differs from the network PLT and may vary dramatically for different types of web pages, e.d. due to the actual implementation, the used plugins, etc.

3. Perceived vs. Application PLT. As we have already seen, there are several factors yielding to non-linear relationships between bandwidth and (network and application) page load time. However, the WQL considers waiting times, i.e. user perceived PLTs. In psychology, it is a well known that subjectively experienced time and objective physical time differ [9]. In addition, in web browsing a page might appear to the end-user to be already loaded although page content is still being retrieved, due to the progressive rendering of the browser, asynchronous content loading (AJAX) and the fact that pages are often larger than the browser window itself. To assess the resulting differences between perceived subjective PLT and application-level PLT, we additionally asked participants in dedicated tasks to mark the point in time when they considered a page to be loaded, i.e. the subjective PLT. Figure 6 shows the ratio of the application-level PLT and the subjective PLT for different page types (and three different pages within each type, e.g. front page, search results and article detail page for Amazon). It can be seen that there are large differences between technical and perceived completion time, with ratios ranging from 1.5 up to 3 (where 1 would be the exact match between subjective and application level PLT).

Summarizing, all these different aspects lead to practical issues and challenges to measure or estimate the waiting time as input for the WQL, even when the WQL hypothesis is valid for web browsing too.

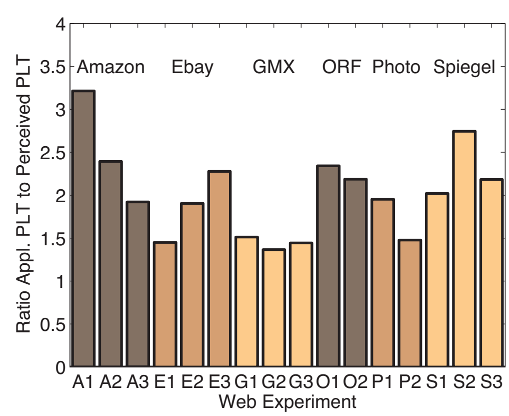

Fig. 6: Perceived subjective vs. application-level PLT for different pages.

V. Conclusion

In this paper we have shown that pure waiting tasks that are typical for simple web usage scenarios (e.g. file downloads) do follow the Weber-Fechner law, given that waiting time is considered as stimulus. For these simple scenarios, bandwidth and resulting waiting time tend to be correlated nearly perfectly, with download bandwidth and object size being sufficient for MOS estimation. In a second step we have tried to directly extend this relationship (between time and MOS) to the more complex case of interactive web browsing. However, two key difficulties prevent such a direct extension: First, the subjective page load time (PLT) perceived by human users does not show a clear correlation with the technical, objectively measured PLT. Second, the relationship between downlink bandwidth and PLT does not follow a straightforward mapping function. Consequently, our title question, "Time is Bandwidth"?, cannot be positively answered in this case. This means that existing web browsing QoE models such as [28], that reduce interactive browsing to a simple request-response transaction with a given waiting time do not sufficiently address the inherent perceptual and technical complexities of this application type. In addition, they do not support the mapping of typical network QoS parameters such as available bandwidth, packet loss or delay to QoE. Thus for future work, we recommend the development of web browsing QoE models that consider a wider range of influence factors and metrics (e.g. page rendering speed, minimum/maximum response time, perceived latency) in order to adequately capture the highly interactive and immersive nature of surfing the web.

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