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The Processing of Frequency and Duration

[Die Verarbeitung von Häufigkeit und Zeit]

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Zusammenfassung

Die Häufigkeit und die Dauer, mit der Ereignisse auftreten, sind zwei grundlegende Merkmale des Geschehens in unserer Umwelt. Sie beeinflussen unser Erleben und Verhalten und wirken sich auf Lernprozesse aus. In vielen Situationen müssen wir in der Lage sein, Unterschiede in Auftretenshäufigkeit und –dauer wahrzunehmen, um angemessen zu reagieren und die richtigen Entscheidungen zu treffen.

In der vorliegenden Arbeit wird die menschliche Verarbeitung von Häufigkeit und Dauer anhand von Häufigkeits- und Zeitschätzungen untersucht. In bisherigen Untersuchungen wurde bereits festgestellt, dass sich die Wahrnehmungen von Häufigkeit und Dauer unter bestimmten Umständen gegenseitig beeinflussen: So werden Häufigkeiten umso größer geschätzt, je länger die entsprechenden Stimuli dargeboten werden; außerdem wird die Stimulusdauer als umso länger beurteilt, je öfter die Stimuli präsentiert werden. Auf der Basis dieser Befunde wurde vermutet, dass der Verarbeitung von Häufigkeit und Zeit ein gemeinsamer Verarbeitungsmechanismus zugrunde liegt. Tatsächlich wurde dies schon im Rahmen tierexperimenteller Studien bestätigt. Weiterhin gibt es neuropsychologische Befunde, die darauf hindeuten, dass Häufigkeit und Zeit in identischen Hirnstrukturen verarbeitet werden.

Allerdings gibt es auch Befunde zur menschlichen Häufigkeits- und Zeitverarbeitung, die die Annahme eines gemeinsamen Verarbeitungsmechanismus in Frage stellt. Diese Studien zeigten eine asymmetrische Beziehung zwischen Häufigkeits- und Zeitschätzungen: Häufigkeitsurteile waren dabei sehr präzise und relativ unbeeinflusst von der Darbietungsdauer, während Zeiturteile wesentlich unpräziser waren und stark von der Stimulushäufigkeit beeinflusst wurden.

Die vorliegende Arbeit ist motiviert durch die Annahme, dass es sich bei dem gefundenen asymmetrischen Beziehungsmuster um einen Forschungsartefakt handelt. Die Ursache für das beschriebene Ungleichgewicht zwischen Häufigkeits- und Zeiturteilen ist vermutlich die Tatsache, dass die Verarbeitung von Häufigkeit und Zeit unterschiedlich viel Aufmerksamkeit benötigt. Die Enkodierung von Stimulushäufigkeiten benötigt nur relativ wenig Aufmerksamkeit. Für eine vollständige Enkodierung der Darbietungsdauer ist hingegen wesentlich mehr Aufmerksamkeit nötig, die über die gesamte Präsentationsdauer des jeweiligen Stimulus‘ hinweg aufrecht erhalten werden muss. In den Studien, in denen ein asymmetrischer Zusammenhang gefunden wurde, wurden meist sehr viele Stimuli ohne spezielle Bedeutsamkeit für die Probanden präsentiert (z.B. Wortlisten). Vermutlich wurde deshalb nur wenig Aufmerksamkeit auf die Stimuli gerichtet, so dass zwar die Häufigkeit, nicht jedoch die Darbietungsdauer, vollständig enkodiert wurde. Die gefundene geringe

Zeitsensitivität sowie die hohen Sensitivität für Häufigkeiten bestätigen diese Annahme. Ein asymmetrisches Beziehungsmuster ist unter diesen Umständen kaum verwunderlich, da zwar die gut differenzierten Häufigkeitsurteile viel Einfluss auf die kaum hinsichtlich der tatsächlichen Darbietungszeit diskriminierenden Zeiturteile haben können, umgekehrt ist dies jedoch kaum möglich. Diese Annahmen werden im Rahmen von drei Manuskripten überprüft.

Im ersten Manuskript wurden die Auswirkungen kognitiver Beanspruchung auf die Häufigkeits- und Zeitverarbeitung untersucht. Die kognitive Beanspruchung wurde hierbei variiert anhand der Anzahl der zu verarbeitenden Stimuli sowie anhand der Aufgabenkomplexität. Eine hohe kognitive Beanspruchung geht dabei mit einer reduzierten Aufmerksamkeit für die einzelnen Stimuli einher. Bei hoher kognitiver Beanspruchung zeigten sich eine niedrige Zeitsensitivität und ein asymmetrisches Beziehungsmuster zwischen Häufigkeits- und Zeiturteilen. Bei geringer kognitiver Beanspruchung hingegen war die Zeitsensitivität höher und die Urteile beeinflussten sich gegenseitig.

Im zweiten Manuskript lenkten wir die Aufmerksamkeit der Teilnehmer zum einen durch die Stimulusart (neutrale Worte versus emotionale Bilder) auf die Stimuli, zum anderen durch eine Aufgabe, bei der die Aufmerksamkeit während der gesamten Stimulusdarbietung auf die Stimuli gerichtet werden musste. Dabei zeigte sich die größte Zeitsensitivität, wenn emotionale Bilder gezeigt wurden und zusätzliche Aufmerksamkeit durchgehend auf die Stimuli gerichtet wurde. In dieser Bedingung fand sich zudem die größte gegenseitige Beeinflussung zwischen Häufigkeits- und Zeiturteilen.

Im dritten Manuskript untersuchten wir den Effekt der Aufmerksamkeit auf die Häufigkeits- und Zeiturteile in realitätsnäheren experimentellen Settings. In der ersten Studie lenkten wir die Aufmerksamkeit der Probanden während der gesamten Präsentationsdauer auf die Stimuli (durch die Darbietung von Straßenverkehrssimulationen, in denen während der gesamten Präsentationsdauer Bewegung zu sehen war). Die Zeitsensitivität war hierbei hoch und Häufigkeits- und Zeiturteile beeinflussten sich gegenseitig. In der zweiten Studie wurde mittels einer Zweitaufgabe Aufmerksamkeit von den Stimuli abgezogen. Je mehr Aufmerksamkeit von den Stimuli abgelenkt wurde, desto geringer war die Zeitsensitivität und desto kleiner die gegenseitige Beeinflussung der Häufigkeits- und Zeiturteile.

Die Befunde deuten allesamt auf einen gemeinsamen Verarbeitungsmechanismus von Häufigkeit und Zeit hin. In der vorliegenden Arbeit wird die Anwendung der gewonnenen Erkenntnisse für Entwicklung eines Erklärungsmodells der menschlichen Häufigkeits- und Zeitverarbeitung diskutiert.

The Processing of Frequency and Duration

Contents

Preface

As long as science exists, we are trying to understand how the human mind works. How do we decide about the content of an impressionist painting consisting of thousands of color dots? How do we recognize a melody composed of a multitude of single tones? To come up with such complex perceptions, we might use information at a more basic level that is, for example, the number and durations of events or objects. We are able to estimate stimulus frequencies and durations, and frequently these judgments are impressively accurate. Interestingly, our estimates are often better than we might think.

Most of the participants in our experiments did not believe that they were able to estimate frequency and presentation duration of a relatively high number of stimuli, which were presented rapidly and in random order. However, in most cases, their judgments were quite good. Even when not processing all features of the stimuli consciously, most of the time, the human mind is capable to produce adequate judgments. To date, we still know little about the specific mechanisms within the human brain that are responsible for creating a remarkable complex and appropriate image of the world. However, scientists from various fields are working together to understand the interactions of the human cognitive processes.

Frequently, basic research leads to the question of potential practical benefits that might be obtained from such basic results. Sometimes this question is hard to answer, especially when the results of research are very specific and – at least at first sight – not assignable to a specific area of practice. Despite the fact that the whole is more than the sum of its parts, we have to identify these parts to understand the whole. Only if we understand how human perception works and how the brain processes information, we are well able to diagnose and treat neurological and psychological disorders, to design our environment to avoid accidents, and to facilitate learning. Science achieved good progress in this field of research within the last decades, but we are far away from a complete understanding of the functions of the human mind.

With trust in the capability of the human brain as well as with persistence in the investigation of its processing mechanisms, we probably will be able to understand the processes within the human mind one day. Scientists assemble the pieces of the puzzle one by one. Despite the fact that sometimes the single elements are tiny and seem to be insignificant to the big picture, each of the pieces brings us closer to the understanding of the human perception. Here comes another piece of the puzzle.

1 Introduction: Research on the processing of frequency and duration

„Reality is merely an illusion, although a very persistent one." (Albert Einstein)

Why should we study frequency and duration processing?

Frequency and duration are fundamental characteristics of the empirical world. Each stimulus in our environment appears for a defined duration, and we experience most of these sensory impressions more than once (e.g., listening to a familiar song on radio). Typically, stimulus duration and frequency are related to the significance of the respective stimulus. For example, if the engine of our car makes clanking noises with increasing frequency and duration, probably a serious problem will be on hand. Hence, we will – presumably with good reason – intervene immediately to avoid a breakdown or an accident. To perceive the events in our daily life adequately, and to be in a position to react in an optimal manner, we have to be able to recognize the frequencies and durations of events correctly. Unlike for the perception of visual stimuli, sounds, odors, taste, and tactile stimuli, we have no special sensory organ for the perception of frequency and duration. Nevertheless, we assume that specialized systems exist within the human mind which account for the processing of this information.

A general characteristic of perception is the gap between objective-physiological sensations and subjective-psychological perceptions. Physical stimulations are received and transferred to the appropriately responsible brain region. These sensations are compared with stored knowledge and linked to other related sensations of the same stimulus (Goldstein, 2007). It is only due to this kind of sensation processing that meaningful impressions of the world are likely to occur. However, a substantial difference between the physical and the perceived stimulus exists. Obviously, to generate an exact image of the complete physical characteristics of our empirical world, a large amount of cognitive resources would be needed. Instead, we are equipped with various heuristics that support the development of an (in most cases) sufficient image of the world. Although misperceptions (e.g., Goldstein, 2007) or cognitive deceptions (e.g., Hell, Fiedler, & Gigerenzer, 1998) might occur when relying on such heuristics, these misinterpretations are an exception in everyday life.

It is no wonder that misinterpretations or biased judgments are frequently examined, although they are not that common, because the detection of these heuristics facilitates a better understanding of the human processing mechanisms which turn physical sensations into perceptions. To know these human processing mechanisms, supports us to design our environment in a manner to avoid defective judgments as far as possible.

In what follows, I will especially discuss the processing of frequencies and durations. Despite the generally highly developed human ability in estimating frequencies and durations (e.g., Cordes, Williams, & Meck, 2007), experimental results demonstrates systematical biases for both kinds of judgments. To examine these biases might give us information about the underlying mechanisms of frequency and duration processing. Although extensive research has already been conducted within this field of research, the results are inconclusive, and a comprehensive model which allows including all results does not yet exist. Hence, the present research examines the factors influencing the processing of frequencies and durations, thus explaining some of the contradictions inherent in previous findings, and providing some first steps toward the development of a comprehensive model of frequency and duration processing.

What do we know about frequency and duration processing so far?

The processing of frequency

As already noted, humans have a highly developed ability in estimating event frequencies (Sedlmeier, Betsch, & Renkewitz, 2002). Frequency processing thereby is a relatively automatic process, which requires only minimal cognitive capacities and low attentional resources. However, there are several factors that affect the quality of frequency estimates.

(1) An important factor influencing frequency judgments is the duration of the stimulus presentations. Within some of the previous studies, an interaction between stimulus frequency and presentation duration was obtained (Hintzman, 2004; Lewandowsky & Smith, 1983; Williams & Durso, 1986), that is, the longer the stimulus durations, the higher the frequency judgments tended to be, even when actual frequencies were in fact held constant. Similar findings were obtained within animal research (Fetterman, 1993; Meck, Church, & Gibbon, 1985).

(2) Another significant factor influencing frequency judgments is the attention directed toward the stimuli during encoding. A series of studies demonstrated that the accuracy of frequency judgments was improved by deeper levels of processing associated with higher amounts of attention directed toward the stimuli (Fisk & Schneider, 1984; Greene, 1984, 1986; Jonides & Naveh-Benjamin, 1987).

(3) Furthermore, there are several other contextual factors influencing frequency judgments. For example, stimuli with spaced repetitions receive higher frequency estimates than stimuli with massed repetitions within a sample of stimuli (e.g., Hintzman, 1969; Hintzman, Summers, & Block, 1975). In addition, higher frequency judgments occur when stimuli are repeated within the same

context rather than in different contexts (e.g., Brown, 1995, 1997). Sedlmeier and Betsch (2002) provide a comprehensive overview on the various characteristics of frequency processing.

The processing of duration

Similar to the human ability of estimating frequencies, humans are able to make remarkably accurate duration judgments (Buhusi & Meck, 2005; Gallistel, 1996; Rammsayer, 2003). However, the processing of durations within seconds or minutes requires more attentional resources as compared to frequency processing. In order to be able to entirely process the presentation duration of a stimulus, attention toward this stimulus has to sustain for the complete stimulus duration (Brown, 1997; Khan, Sharma, & Dixit, 2006; Rammsayer, 2003). As in the case of frequency judgments, there are several factors that influence duration judgments.

(1) One important factor influencing duration judgments is the frequency of stimulus presentation. In almost every study on the impact of stimulus frequency on duration estimates, we find duration judgments to be longer when stimulus frequencies increase, even though presentation duration was in fact held constant (e.g., Block, 2003; Hintzman, 1970). Similar findings were obtained within animal research (Fetterman, 1993; Meck & Church, 1983).

(2) Another factor influencing duration judgments is the amount of attention directed toward the stimuli during encoding. Thereby, as already noted, it is not only the intensity of attention that exerts an influence, but also its (uninterrupted) presence. In order to be able to generate accurate duration judgments, a person needs to attend to this stimulus for the complete stimulus duration. The assignment of a dual task paradigm is an often used experimental method to distract attention from the stimulus processing, and thus, to examine the effect of attention on duration processing. If attention is distracted from the stimuli, duration judgments are getting shorter and less accurate (Brown, 1997; Brown & Boltz, 2002; Khan et al., 2006).

(3) A variety of additional factors influencing duration judgments were obtained, as for example personal characteristics (e.g., the person's temporary arousal; see Zakay & Block, 1997, or age; see Block, Zakay, & Hancock, 1999) and features of the situation (e.g., the complexity of the stimuli presented; see Ornstein, 1969). It is interesting that these factors hardly have an impact on the quality of frequency judgments (Hasher & Zacks, 1984), which demonstrates that frequency judgments are generally less prone to biases as compared to duration judgments.

A model that is able to explain most of the findings on duration judgments is the attentional-gate model (Zakay & Block, 1996, 1997). Duration judgments, according to these authors, are based on an internal pacemaker. To generate duration judgments of an event, the number of accumulated pulses in working memory is compared with stored time spans in the reference memory. When the presence of an event is not in the focus of individual attention, pulses go unrecognized during the counting process. This leads to an underestimation of stimulus duration. As a consequence, any factor that directs attention toward the stimuli should enhance the sensitivity to stimulus duration. A second factor within the attentional-gate model is the pulse rate of the pacemaker, which is influenced by a person's arousal. Hence, when the arousal of the person is high, more pulses are produced within the same time span, and thus, event durations might be overestimated.

However, this model is applied only to prospective time estimation, i.e., duration processing with the knowledge that time estimates are needed. Within most of the mentioned studies, participants did not know in advance that they were required to estimate stimulus durations (retrospective time estimation). According to Zakay & Block (1997), different processing mechanisms are underlying prospective and retrospective time estimates. Hence, the model (at least in its present form) is not applicable to all findings on human time perception. It remains to be seen whether the existing concepts can be extended in a way that allows for a development of a comprehensive model of human time perception.

The mutual interaction between frequency and duration processing

Based on what we know about the factors on the processing of frequency and duration, two conclusions can be drawn: (1) Stimulus frequency and presentation duration influence each other mutually, at least under certain conditions. (2) Both judgments of frequency and duration are enhanced (although to a different extent) when attention to the respective stimuli is increased. This leads to the assumption that one common mechanism is underlying the processing of frequency and duration.

Actually, various findings exist that point in this direction, suggesting a common mechanism underlying both frequency and duration judgments: Within animal research, there is ample evidence that time and number are processed by the same mechanisms (for an overview, see Brannon & Roitman, 2003). To account for the similarities within frequency and duration processing, Meck and Church (1983) postulated a mode-control model (see Figure 1.2). In this model, a pacemaker emits pulses that are summarized by an internal accumulator. A mode switch allows the system to work as a timer or counter. When the switch operates in the *run* or *stop mode*, it serves as a timer. Pulses are gated to the accumulator as long as an event is attended to. In contrast, when the switch operates in the *event mode*, it works as a counter. Whenever a certain event occurs, pulses are gated to the accumulator for a fixed interval. The stored values of the accumulation processes will then be compared to existing values of a definite time span or a certain quantity stored in the reference memory. Thus, the accumulated value provides a common currency for duration and frequency representation and, using multiple switches and accumulators, the individual will be able to quantify duration and frequency simultaneously.

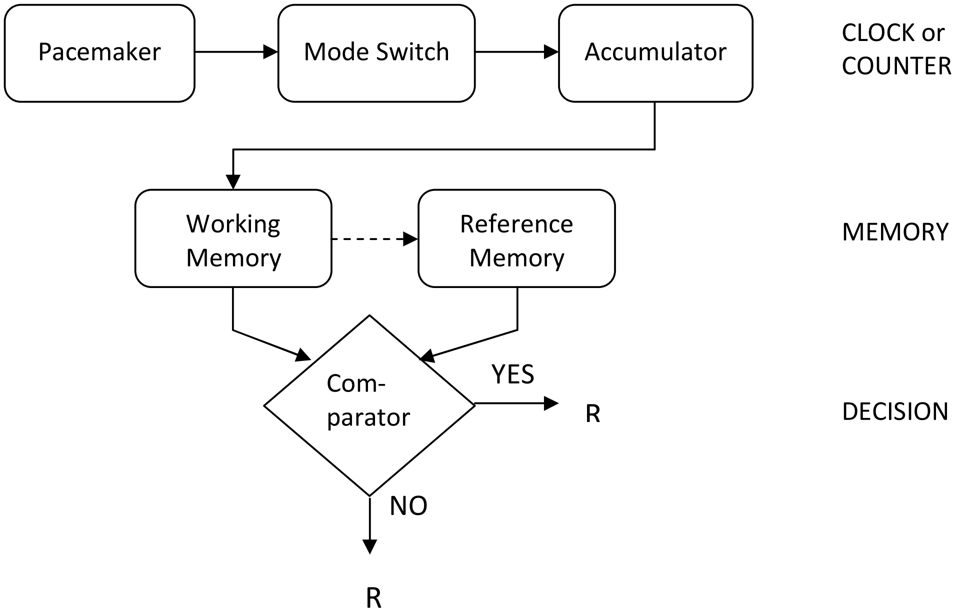

Figure 1. Mode-Control Model (Meck & Church, 1983).

In a similar vein, a common magnitude-representation system of the perception of frequencies and durations has been suggested for humans as well (Walsh, 2003). Neuropsychological research supports this assumption (Cordes et al., 2007), and a common neural basis has been identified (the thalamo-cortico-stratial circuits) that is shared by both frequency and duration processing (Buhusi & Meck, 2005).

However, as already mentioned, conflicting results have been obtained within human behavioral research, which challenge the validity of a common processing unit. For example, in a series of studies, Hintzman (1970) and Hintzman et al. (1975) varied frequencies and durations for a large number of words, allowing for an analysis of the interaction between frequency and duration processing. An asymmetrical result pattern for judgments of frequency and duration was an unexpected but reproducible finding: Frequency judgments were relatively accurate and uninfluenced by presentation durations. However, duration judgments were not as accurate and strongly influenced by stimulus frequencies.

Due to this inconsistency within the findings of previous studies, further research was needed to clarify the conditions of the mutual interaction between frequency and duration processing.

Open questions and outline of the present research

The present research investigates the causes of the divergent results described above. By means of three series of experiments, which are summarized within three manuscripts, it is examined under which conditions an asymmetrical relationship between frequency and duration processing occurs. Furthermore, it is analyzed, by means of the simultaneous manipulation of stimulus frequency and duration, under which conditions a mutual interaction (as obtained in previous studies) might be replicated.

These investigations are based on the assumption that the exclusively (predominantly) asymmetrical relationship between frequency and duration are caused by a research artifact. This artifact presumably occurred due to the fact that the processing of frequency and duration has different attentional demands. The processing of frequency requires only minimal attentional resources (Hasher & Zacks, 1984), in fact just for the moment of stimulus onset. However, duration processing requires more attention, which has to sustain for the complete presentation duration of the stimulus. If participants focus their attention just briefly on the stimuli, namely whenever a new stimulus is presented, and if these attentional resources are decreasing immediately during the stimulus presentation, stimulus frequencies – but not stimulus durations – would be encoded adequately. As a consequence, frequency judgments would be accurate, while judgments of duration would not discriminate between the actual stimulus durations – a result pattern actually obtained by Hintzman (1970), and Hintzman et al. (1975).

Furthermore, when assuming that there exists one common mechanism for the processing of frequencies and durations, it is hypothesized that the perceptions of frequency and duration will mutually influence each other. Due to the extreme differences between the sensitivities to stimulus frequencies versus presentation durations, an imbalance within the interaction between frequency and duration processing might emerge, based on the following assumptions: (1) Frequency perceptions are quite accurate and differ strongly between actual differences in stimulus frequencies. (2) Duration perceptions, however, are hardly discriminating based on actual stimulus durations. (3) Thus, frequency perceptions would not be modified by perceived presentation durations, due to the fact that the latter might differ only little from each other. (4) However, duration perceptions would be influenced by the perceived stimulus frequencies to a much higher extent, because the frequency perceptions differ strongly based on the actual variations in stimulus frequencies. To examine whether there actually is one common mechanism underlying the processing of frequencies and durations, one has to analyze the interaction between frequency and duration processing, given the requirements for the entire encoding of stimulus frequencies as well as presentation durations. This is the aim of the present research.

Research design

Each of the present studies is based on the same principal research paradigm. The participants were presented stimuli in random order that varied in presentation frequency (e.g., 2 times, 4 times, or 8 times) and in presentation duration (e.g., 2 sec, 4 sec, or 8 sec) on three levels each. After the complete stimulus presentation, participants were required to estimate stimulus frequency and presentation duration of each stimulus. Participants' sensitivity to stimulus frequencies and presentation durations was examined. Furthermore, the interaction between frequency and duration processing was analyzed, that is, the strength of the effect of stimulus frequencies on duration judgments, and the strength of the influence of stimulus durations on frequency judgments.

Manuscript 1: The effects of cognitive load on the simultaneous processing of frequency and duration

The studies that obtained an asymmetrical interaction between frequency and duration processing had one notable similarity, which differentiated them from the animal research (revealing a mutual interaction pattern between frequency and duration judgments): A high number of stimuli were presented, resulting in a high cognitive load. In the study of Hintzman (1970), for example, 84 three-letter nouns varying with respect to stimulus frequency and presentation duration were presented. Subsequently, participants were required to generate frequency and duration judgments. Due to the fact that frequency processing requires only little attention, frequency judgments were fairly accurate. However, the attentional resources were presumably too low for sufficient duration processing, due to the high cognitive load of the experimental task. Cognitive load directly covaries with the number of items or processing stages stored in working memory (Sweller, 1988; Tuovinen & Sweller, 1999). Thus, a high cognitive load of a task reduces the attentional resources available for other cognitive demands. The obtained low sensitivity to stimulus duration as well as the asymmetrical result pattern between frequency and duration judgments might have been the consequence of such a high cognitive load. In Manuscript 1, the effect of cognitive load on the interaction between frequency and duration processing is analyzed. It is examined (a) whether an asymmetrical relationship between frequency and duration is replicated under conditions of high cognitive load, and (b) whether a mutual interaction is obtained under conditions of low cognitive load.

Within two studies, the cognitive load of the experimental task was varied, and the effects on sensitivity to stimulus durations as well as on the interaction between frequency and duration processing were examined. Therefore, the number of presented stimuli was varied, and the complexity of the task was manipulated by requiring the participants to either generate judgments of single stimulus durations or of total presentation durations of each (repeatedly presented) stimulus. In Study 1, either a high number of stimuli (36 first names) or a low number of stimuli (9 first names) was presented. Participants were required to estimate stimulus frequencies and single stimulus durations. In Study 2, likewise either 36 or 9 first names were presented. However, participants were required to estimate stimulus frequencies and total presentation durations of the stimuli, that is, the accumulated presentation duration of each single stimulus presentation. Estimating the total stimulus durations is the more complex task (and thus, induces a higher cognitive load), due to the fact that participants had to aggregate their stored perceptions of each single presentation duration.

The results show that both the number of stimuli as well as the task complexity (judgment about a single stimulus versus about aggregated stimuli) had an effect on the interaction between frequency and duration processing. When presenting a small number of stimuli, or when requiring judgments of single stimulus duration, result patterns are more symmetrical. As could be expected, the strongest mutual interaction between frequency and duration was obtained within the condition involving a small number of presented stimuli and requiring only single duration judgments.

Manuscript 2: The impact of intrinsic and extrinsic attention on frequency and duration processing

Within the studies that obtained an asymmetrical interaction between frequency and duration processing, participants were not only presented a high number of stimuli, but also received relatively simple and irrelevant stimuli that presumably attracted only a small amount of the participants' attention. Hintzman (1970) for example, presented his participants abstract three-letter nouns. Probably, such stimuli attract the participants' attention only briefly. Thus, attention is assumed to be attracted by each stimulus onset and decreases rapidly during the stimulus presentation. Given that these considerations are correct, the obtained difference between sensitivity to frequencies and sensitivity to durations as well as the asymmetrical relationship between frequency and duration judgments is exactly what we would expect. Stimulus frequencies would be encoded entirely, and thus, frequency judgments should be relatively accurate. However, attentional resources were probably not sufficient (neither the amount nor the persistence of attention) to facilitate the entire encoding of presentation durations. Therefore, the obtained low sensitivity to durations as well as the asymmetrical result pattern in Hintzman's study do not come unexpected.

Within the study described in Manuscript 2, the effect of attention on frequency and duration processing is analyzed. It is examined whether an increased sensitivity to stimulus durations and a mutual interaction between frequency and duration processing occurs when attention is directed toward the stimuli. To do so, we used two different methods. First, we varied the amount of intrinsic attention toward the stimuli, by either presenting stimuli low in emotional relevance (first names) or stimuli high in emotional relevance (highly emotional pictures from the International Affective Picture System, IAPS; Lang, Bradley, & Cuthbert, 2005). It is supposed that participants focus their attention toward emotionally relevant stimuli more strongly. Second, the amount of extrinsic attention was manipulated by requiring the participants to lift a dumb bell whenever, and as long as, a stimulus of a certain category was presented. Therefore, participants were required to focus their attention toward the stimuli during the complete presentation duration of the respective stimulus. Due to the fact that lifting a dumb bell is quite straining, the stimulus durations probably are extremely relevant to the participants. It is supposed that both methods of attention direction promote a higher sensitivity to durations as well as a mutual interaction between frequency and duration processing.

The results support these hypotheses. The strongest effect on the sensitivity to durations and on the interaction between frequency and duration occurred within the condition of emotionally relevant stimuli and the additional requirement of lifting a dumb bell.

Manuscript 3: The effects of attention focusing and shared attention on the processing of frequency and duration

Due to the fact that the studies presented in Manuscript 1 and 2 used relatively artificial contexts, it was the aim of the experiments described in Manuscript 3 to analyze frequency and duration judgments in more realistic settings. The two studies described therein employed realistic situations, and the impact of attention on frequency and duration processing was analyzed in order to increase the external validity of the results.

In Study 1, participants either watched a video of traffic simulations, reconstructing typical situations within road traffic in a highly realistic way. These simulations consisted of different kinds of waiting situations (e.g., red lights with crossing traffic), which were presented either this way (as film) or as fixed images of the very same situations. Due to the fact that the stimuli within the traffic simulations are in permanent motion, they are assumed to attract more attention during the complete presentation duration as compared to the fixed images. In contrast, the images are relatively simple, and therefore, are assumed to attract the participants' attention only briefly (i.e., at stimulus onset). Results indicate a stronger sensitivity to durations for the traffic simulations as compared to the fixed images of these situations. Furthermore, within the fixed-image condition, an asymmetrical relationship between frequency and duration processing was obtained, with accurate and unbiased frequency judgments and strongly biased duration judgments. In contrast (and as expected), frequency and duration judgments influenced each other mutually within the traffic-simulation condition.

In Study 2, participants saw promotional images (referred to as ‘pop ups’) that appeared abruptly on the computer screen with specific frequencies and durations (as known from the internet). Participants either received different attention absorbing secondary tasks, or no additional task (control condition). In both cases, participants were instructed to monitor the various pop ups. Within two dual-task conditions, participants were either required to carefully read an article or to watch a documentary, while the pop ups repeatedly covered the screen for a short time interval. Reading the article was assumed to distract the highest amount of attention from the stimuli (the pop ups), because participants had to interrupt reading and to memorize the read content during the pop-up presentations. The cognitive resources, therefore, have to be shared between stimulus processing and memorizing the content of the article. However, watching a documentary was assumed to distract less attention from the stimuli, because the participants were still able to follow to the sound of the documentary, while pop ups covered the screen from time to time. Within the control condition, presumably the largest attentional resources were available for the processing of frequencies and durations. It is assumed that the more attention is distracted from the stimuli, the lower the sensitivity for durations as well as the mutual influence between frequencies and durations is.

By and large, the results support these hypotheses. The strongest sensitivity to stimulus durations was obtained in the control condition without any secondary task (and therefore, without any attention distraction). The mutual influence between frequencies and durations was stronger when less attention was distracted from the stimuli.

The three chapters that follow consist of the Manuscripts 1 to 3 in their original form, as submitted or ready for submission at peer reviewed psychological journals. The last chapter gives a brief summary and discusses the implications of the present findings with respect to the development of a comprehensive model of frequency and duration processing.

2 Can too much information put us out of time? The Effects of Cognitive Load on the Simultaneous Processing of Frequency and Duration

Can too much information put us out of time?

The Effects of Cognitive Load on the Simultaneous Processing of Frequency and Duration

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Abstract

Previously in a series of studies on the perception of frequency and duration in humans, an asymmetrical relationship was found: While frequency judgments were quite accurate and independent of stimulus duration, duration judgments were highly dependent upon stimulus frequency. The present data suggest that this frequently observed effect is moderated by differences in cognitive load. In two experiments, participants processed stimuli with varying presentation frequencies and durations. In addition, the total number of stimuli was varied, thus establishing conditions with high versus low cognitive load. An asymmetrical relationship between stimulus frequency and duration was found under high cognitive load, with duration estimates being influenced by stimulus frequency. For low cognitive load, however, participants revealed a higher sensitivity to stimulus duration, and an interdependence between frequency and duration judgments was found. Results are discussed with respect to mechanisms underlying the simultaneous processing of frequency and duration.

Imagine being a physician in a hospital, taking care of seriously ill patients. Perhaps one is hospitalized with the complaint of a racing heart. To do your job, you would have to know how many times this patient's symptoms have already occurred and how long each episode lasted. In many cases, a correct diagnosis and, ultimately, the right treatment crucially depend on good estimations of duration and frequency. How good do you think your perception would be? Could you trust your judgment, or would it be biased, especially because you would have to work under extreme time pressure, while simultaneously dealing with many different competing concerns? To answer these questions, we need to understand how the human mind processes frequencies and durations of events.

Both frequency and duration are central elements of our experience and behavior (e.g., Gallistel, 1989; Walsh, 2003). In everyday life, our regular reliance on our perceptions of time and frequency (Fiedler, 2002; Meck, 2003) is reflected in the decisions we make, and it has been shown that the experience of event frequencies and durations is highly important in adaptation and learning processes (Balsam, Fairhurst, & Gallistel, 2006; Jonides & Naveh-Benjamin, 1987; Meck, 2003). Thus, in many situations, we have to notice differences in stimulus frequency and duration in order to react and decide appropriately.

Humans exhibit impressive accuracy in estimating stimulus frequencies. Without intentionally counting, we are able to make remarkably good frequency judgments – even under stress, under high levels of arousal, and with simultaneous cognitive demands (Gallistel & Gelman, 1991; Hasher & Zacks, 1979, 1984; Zacks & Hasher, 2002). There is impressive evidence that human adults are sensitive to the frequencies and relative frequencies of a wide range of different stimuli (Sedlmeier & Betsch, 2002) – such as pictures (Ghatala, Levin, & Wilder, 1973; Hintzman, Curran, & Caulton, 1995), category labels (Brown, 1995, 1997), words (Dougherty & Franco-Watkins, 2003; Hintzman, 1969, 1970), syllables (Underwood & Zimmerman, 1973), single letters (Attneave, 1953), letter positions (Sedlmeier, Hertwig, & Gigerenzer, 1998), and flashing dots (Dormal, Seron, & Pesenti, 2006; Whalen & Gallistel, 1999). Remarkably, the encoding of frequencies seems to work fairly automatically and requires only minimal attention (Johnson, Peterson, Yap, & Rose, 1989; Zacks & Hasher, 2002).

Similar to our sensitivity to event frequency, our highly developed sensitivity to durations thrives even when external time cues are absent (Gallistel, 1990, 1996). Like most animals, we are capable of processing and differentiating temporal information across a wide range of intervals – from circadian timing to the timing of minutes, seconds, and, milliseconds (Buhusi & Meck, 2005) – and modalities, for instance, visual and acoustic stimuli (Penney, Gibbon, & Meck, 2000). Whereas the perception of very short durations seems to be extremely accurate (e.g., Rammsayer, 2003), judgments about time intervals in the range of seconds to minutes can be strongly influenced by attentional processes

(Block, 2003; Zakay, 1989; Zakay & Block, 1996). The latter kind of judgment also seems to be determined by some kind of internal rhythmic mechanism, a *pacemaker* (for some evidence see Rammsayer, 2003; Wearden, 2003). The idea of such a pacemaker is included in prominent models of time perception (e.g., Church & Broadbent, 1990; Wearden, 2003; Zakay & Block, 1997). According to these models, the number of accumulated pulses in working memory needs to be compared with stored time intervals in the reference memory to generate duration judgments of an event. The pulse rate of the pacemaker can be influenced by arousal, so event durations might be overestimated when arousal is high (and thus, more pulses are produced within a certain time span) or underestimated when timing perception is not the focus of individual attention (hence, pulses go unrecognized during the counting process). Thus, in contrast to event frequency, stimulus duration is not processed automatically but rather seems to require a certain amount of attentional resources (Dormal et al., 2006).

The Simultaneous Processing of Frequency and Duration

Although there are differences in attentional demands regarding the processing of time and frequency, both are elementary aspects of our cognitive processes so one may wonder whether they rely at least partially on common mechanisms. Indeed, connections between the perception of time and number have been noted since at least 1890 (see Walsh & Pascual-Leone, 2003). We also find more recent evidence from brain research indicating that there are neuronal circuits involved in judgments of both duration and frequency (Buhusi & Meck, 2005; Dormal et al., 2006; Walsh, 2003). But is there behavioral evidence supporting this assumption? To date, this question has been addressed predominantly in animal research and much less with human participants. And although there are attempts to incorporate the connection between duration and frequency in models that explain human judgment (e.g., Hintzman, 2004), much more theorizing has been done in the animal realm. Interestingly, the picture arising from animal research is quite different from what has been found with human participants. We will first summarize results from both research traditions and then contrast the two collections of findings.

Judgments of Frequency and Duration in Animal Research

Meck and Church (1983) postulated a *mode control model* with a pacemaker that is common to different species and is especially designed for the discrimination of stimulus frequencies and durations. This pacemaker emits pulses that are summarized by an internal accumulator and eventually stored in memory. According to Meck and Church, a switch controls the accumulation process. When the switch operates in the run or stop mode, it serves as a timer. Pulses are gated to the accumulator as long as an event is attended to. In contrast, when the switch operates in the event mode, it works as a counter. Whenever a certain event occurs, pulses are gated to the accumulator for a fixed interval. The stored values of the accumulation processes will then be compared to existing values of a definite time span or a certain quantity stored in the reference memory. Meck and Church (1983) assumed that both kinds of judgments (frequency and duration) are based on one common cognitive mechanism (see also Cordes, Williams, & Meck, 2007). This conclusion is mainly derived from the common finding in animal research that event frequencies exert an influence on judgments of stimulus duration, and stimulus duration also influences judgments of stimulus frequency (Fetterman, 1993; Meck, Church, & Gibbon, 1985).

Research with Human Participants

Data with human participants are not as conclusive as those obtained from animal research. There is an enormous literature on human frequency processing (for an overview, see Sedlmeier & Betsch, 2002). Moreover, research on time perception is also quite extensive (for a summary, see Helfrich, 2003). However, experiments simultaneously analyzing the processing of frequencies and durations (as well as their interdependence) are very rare.

In probably the first study of its kind, Hintzman (1970, Experiment 3) required participants to estimate the frequency and duration of word presentations by varying both stimulus duration (on five levels: 2–6 s) and stimulus frequency (also on five levels: zero to five repetitions), using 84 three-letter nouns. In contrast to findings from animal research, an asymmetrical pattern for judgments of frequency and duration (of a single stimulus presentation) was found: While duration judgments were not as accurate and strongly influenced by stimulus frequency, frequency judgments were relatively accurate and only slightly influenced by varying stimulus durations. Similarly strong effects of frequency on judgments of duration but small effects of duration on frequency estimates were also found in later studies (Hintzman, 2004; Hintzman, Summers, & Block, 1975).

Recently, Betsch, Glauer, Renkewitz, Winkler, and Sedlmeier (2009, Experiments 1 to 4) reported a series of experiments analyzing the effects of stimulus frequency (two to eight repetitions) and total presentation duration (8–24 s) on frequency-of-occurrence judgments of 36 first names and set-size judgments for 18 categories. Participants judged stimulus frequency – either *frequency of occurrence* of a given stimulus or the *set size* (i.e., the number of presented exemplars belonging to a given category) – as well as total presentation duration. Even when directing the participants' focus to duration (by informing them that time estimates would be required subsequently, or by requiring the participants to press a button for as long as each stimulus occurred), time estimates were not as accurate as frequency judgments. Presentation duration had almost no effect on frequency estimates – neither for frequency-of-occurrence judgments, nor for set-size judgments – whereas stimulus frequency systematically biased duration judgments. Thus, as in Hintzman's (1970, 2004) investigations, an asymmetrical pattern of frequency and duration was observed.

In contrast, Williams and Durso (1986) found that presentation duration systematically biased frequency estimations. These authors examined the effect of encoding time of category exemplars on frequency estimations of six different categories (set-size judgments). Stimulus duration was varied between subjects at three levels (0.5–6 s). The authors apparently did not collect duration judgments but found an effect of duration on frequency judgments: The longer each category exemplar was shown to the participants, the larger was the estimated size of the category. These results hint at a symmetrical relationship between frequency and duration.

What Might be the Reason for These Discrepant Results?

Taken together, results from research in humans are inconsistent within themselves and also with empirical evidence based on animal research. We suggest two possible explanations for this discrepancy: first, differences in the meaningfulness or relevance of the stimuli used, and second, the extent of cognitive load induced by the experimental setup.

Stimulus relevance. If we take a closer look at the experimental settings induced in the investigations described above, we find that different kinds of stimuli have been used in animal versus human research. Usually, animals perform a discrimination task under conditions of subsequent reinforcement. Thus, through the association with food, the stimuli to be discriminated are quite meaningful to the animals. Human participants, however, typically make judgments concerning word lists or syllables having no special relevance to them. Therefore, these stimuli might not be significant enough to hold the participants' attention for any length of time. If this is the case, different mechanisms might be at work in animals versus humans in processing frequency and duration, depending on the relevance of the stimuli.

The importance of stimulus relevance is shown in Experiment 5 of Betsch et al. (2009). In contrast to other studies, in this experiment photographs of category exemplars for set-size judgments of frequency and duration were used instead of words or first names. The presentation of photographs improved the sensitivity to total presentation duration as well as for single stimulus duration. Notably, stimulus duration had an effect on frequency judgments, which indicates that more realistic – and therefore presumably more relevant – stimuli might yield a more symmetrical relationship between judgments of frequency and duration.

In a further study, Winkler and Sedlmeier (2009, Experiment 1) required participants to watch a traffic video, prompting them to imagine driving a car and experiencing different waiting situations with specific frequencies and presentation durations. Again, a symmetrical relationship between frequency and duration judgments was observed. We conclude that the use of subjectively relevant stimuli and realistic experimental settings increases the sensitivity to stimulus durations, which, in turn, influence frequency processing.

As these investigations show, the relevance of the stimuli seems to be one powerful factor moderating the interdependent effect in the processing of frequency and duration. But there is another possible factor that could explain these apparently contradictory findings.

Cognitive load. The experimental requirements, producing either high or low cognitive load, is a second important difference between the studies mentioned above, especially between animal research and investigations with human participants. Typically, animals learn to press a button to discriminate *on-target* between frequencies or presentation durations of sensory perceptions, such as tones or light signals. On-target discrimination means that the animal decides whether these stimuli reached either a certain frequency or total presentation duration *directly* after the presentation of a cycle of stimuli. Human participants, in contrast, are typically asked to generate verbal judgments of frequency and duration after the presentation of a number of words or pictures (*off-target*). Thus, participants first have to store the features of the exposed stimuli in memory and then make the corresponding judgments. Hence, a comparatively high cognitive load is induced in most research with human participants by the higher amount of information that must be handled and the need to store this information in working memory (Baddeley, 1992).

Cognitive load results from the limited capacity of our working memory (Miller, 1956). Cognitive processes, such as storing stimuli, comparing them, and making judgments, require short-term capacity that can be affected by cognitive load (Baddeley, 1992). Cognitive load is directly correlated with the number of items or processing stages stored in working memory (Sweller, 1988; see also Mayer, 2005; Tuovinen & Sweller, 1999). So, in judgment tasks, both an increasing number of items and an increasing task complexity (defined by the number of necessary processing steps) increase cognitive load. High cognitive load, in turn, decreases the selective attentional resources available for other simultaneous tasks. Because of the different amounts of cognitive load induced by the experimental demands, attentional resources available to encode the duration of events might have been sufficient for animals in their relatively simple tasks but not for human participants who usually had to deal with a multitude of stimuli and had to perform quite complicated estimation tasks. For instance, in Hintzman's (1970) experiments, participants had to process 84 three-letter words with varying frequencies and presentation durations, and in the experiments of Betsch et al. (2009), the total duration of each of 36 repeatedly presented first names had to be estimated. This might explain the asymmetrical result pattern typically found in those studies: If cognitive load is high, frequencies might still be encoded very well (because their encoding only requires minimal attentional resources) but participants might have no longer been able to attend sufficiently to the duration of stimuli.

In this paper, we will empirically test this second explanation: We assume that cognitive load moderates (a) the sensitivity to stimulus duration and (b) the impact of stimulus duration on frequency judgments. What differences in the judgments should we expect, depending on the amount of cognitive load? For frequency judgments, cognitive load should not play an important role because frequency estimation requires only little attention. Whether cognitive load is high or low, therefore, should not make much of a difference. Judgments of duration, however, need more attentional resources and thus should mimic actual durations better when cognitive load is low rather than high. Under conditions of high cognitive load, duration is hypothesized to be only imperfectly encoded and therefore, the impact of actual frequencies (which can be expected to be well encoded irrespective of the amount of cognitive load) should be stronger. The duration of an event, on the other hand, can only have a systematic influence on frequency judgments if it is encoded properly, which is more probable under conditions of low cognitive load, and hence the impact of duration on frequency can be expected to be more pronounced in conditions with low than with high cognitive load.

In two experiments we induced either high or low cognitive load by varying the number of stimuli presented to participants. In the literature mentioned above, duration estimates have focused either on the duration of a single stimulus presentation (e.g., Hintzman, 1970) or on the total duration of a repeated stimulus presentation (e.g., Betsch et al., 2009). Duration judgments of a single stimulus require fewer processing steps and therefore induce lower cognitive load than judgments of total presentation duration that need more buffer storage, because participants first have to store the single presentation duration of each stimulus and then aggregate the respective values. We conducted an experiment for both types of dependent measures: In Experiment 1 we analyzed judgments of single stimulus presentations; in Experiment 2 we investigated judgments of total durations.

Experiment 1

We systematically varied stimulus frequency and duration for either 36 stimulus words (in the high cognitive load condition) or 9 stimulus words (in the low cognitive load condition). For a given stimulus, the duration was held constant across the whole presentation phase. Participants were required to estimate presentation frequency and duration of a single stimulus (*single stimulus duration*).

Method

Participants. Ninety-six undergraduates (41 female; mean age: 24 years, *SD* = 4.1) from different majors at the Chemnitz University of Technology participated in the experiment and were paid €5.

Material. Stimuli were either 36 different first names on a computer screen (see Appendix) or a random selection of 9 first names from this list. For name selection we referred to a study by Rudolph and Spörrle (1999; see also Rudolph, Böhm, & Lummer, 2007) that collected ratings for how popular and modern first names were considered to be. We selected names that scored within the second and third quartile in popularity and were rated as being relatively modern. In a second step, we tested the names for readability. Specifically, we ensured that names could be easily read aloud and had a similar length (two syllables). The word list consisted of female and male first names, which were counterbalanced to ensure equivalent prevalence, popularity, and readability. The presentation of stimuli and the assessment of dependent measures were controlled by a computer program (E-Prime software, Psychology Software Tools, Inc., 1996), run under a Windows XP environment with 17" monitors.

Procedure. All participants were individually tested in separate cubicles. Upon arrival, they were informed that they would watch a list of words appearing consecutively on the computer screen, and that they would subsequently be asked questions about the presented stimuli. No hint was given that participants would be required to produce frequency and duration judgments. For each individual session, the program randomly drew names from the base list to build a stimulus sample. Male and female names appeared equally often in each condition, and no name appeared twice in immediate succession. We ensured encoding of the stimuli by requiring the participants to read each stimulus word aloud (Johnson et al., 1989). To foster compliance with this instruction, we installed microphones in the cubicles and informed participants that their utterances would be recorded. During a training phase, participants were familiarized with the presentation format and the read-aloud procedure. This training lasted 2 min and used words that were not included in the subsequent experimental trials.

Participants were randomly assigned to one of two between-subjects conditions, high or low cognitive load. Within subjects, presentation frequency and duration were varied in three steps each. First names, therefore, were repeated either 2, 4, or 8 times, and each single presentation lasted either 2, 4, or 8 s. This means, for example, that if a stimulus was in the 4 times/8 s condition, it was shown 4 times for 8 s each. In the high cognitive load condition, four names (two female and two male) in each of the 9 frequency-duration combinations (3 frequencies × 3 durations) were applied, and in the low cognitive load condition, only one name (female or male, randomly chosen) was utilized per combination.

After the stimulus presentation, participants judged the frequency and single presentation duration of each name. For both judgment tasks, the presented stimuli were shown again on the computer screen in a random order. One half of the participants were first asked to estimate presentation frequency of each stimulus and subsequently to estimate stimulus durations. The order was reversed for the other half of participants. For both kinds of judgments, participants were explicitly informed about the lowest and the highest possible values. This procedure was followed to prevent participants from using different estimation standards and, in turn, from producing extreme judgments. The whole procedure took about 20 min.

Results

For the main analyses, we calculated repeated-measures contrast analyses (see Rosenthal, Rosnow, & Rubin, 2000). To test participants' sensitivity to frequency and the impact of actual frequency on judgments of duration, we assigned contrast weights of −4, −1, and +5, according to the variation in presentation frequencies (2 times/4 times/8 times). The same weights were used for examining the impact of the actual durations (2 s/4 s/8 s) on judgments of duration and on judgments of frequency. To obtain more reliable measures, we always averaged over the z-transformed values of the non-focal variable (per level of that variable). For example, when examining the impact of actual frequencies on frequency judgments, we first z-transformed (per participant) all judgments for stimuli that had been presented for 2 s, all that had been presented for 4 s, and all that had been presented for 8 s. And then (again per participant) we calculated the average of all z-transformed judgments for a given presentation frequency (2 times, 4 times, and 8 times). Another example: To check whether actually presented frequencies had an impact on judgments of duration, we performed the z-transformation for each level of frequency (instead of each duration level, as explained above) and averaged duration judgments over each frequency level. Thus, in each analysis, each participant provides three aggregated judgment points.

In repeated measures contrast analyses, the fit between a hypothesis (conveyed by the contrast weights) and the data for a given participant is expressed in a single value, most commonly an L value (Rosenthal et al., 2000, pp. 128–130). In our case, an L value is calculated as the dot product of the weights for a given hypothesis and the corresponding aggregated judgment points.[1] Using these L

values, we computed contrast analyses for (1) the sensitivity to stimulus frequency, (2) the sensitivity to stimulus duration, (3) the influence of stimulus frequency on duration judgments, and (4) the influence of stimulus duration on frequency judgments. As a measure of effect size, Hedges's *g* was used throughout (Rosenthal et al., 2000; Sedlmeier & Renkewitz, 2007).

Sensitivity to stimulus frequency. Frequency judgments systematically covaried with actual presentation frequencies in both conditions – under low as well as under high cognitive load, illustrated by the huge effect sizes in Table 1. We compared the sensitivity to stimulus frequency between high and low cognitive load by means of a between-groups contrast analysis (which, in this case with two groups, is identical to a between-groups *t* test), again using the *L* values for frequency judgments. Under high cognitive load, frequency estimates followed the pattern of relative differences given by the contrast weights even better than under low cognitive load (Table 1, Difference). Despite the high sensitivity to stimulus frequency, the raw data revealed that low frequencies (two repetitions) were generally overestimated (with a mean of 3.0), while high frequencies (eight repetitions) were underestimated (with a mean of 5.9). The most accurate frequency judgments were obtained for the condition providing four repetitions (with a mean of 4.3). This tendency toward the mean is well known in research on frequency processing (Fiedler, 1991; Hintzman, 1969; Sedlmeier et al., 1998). Taken together, the results indicate that the participants were capable of reliably differentiating the repetition frequencies of 9 as well as 36 first names.

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[1] The *L* value for analyzing the sensitivity to presentation frequency, for example, is calculated for each participant by the dot product of the contrast weights (−4, −1, and +5) and the *z*-transformed and aggregated (over the three duration levels) frequency judgments for each level of actual stimulus frequency: $L = -4 \times z(M_{\text{freq2}}) - z(M_{\text{freq4}}) + 5 \times z(M_{\text{freq8}})$ [e.g., $z(M_{\text{freq2}})$ is the aggregated *z*-transformed frequency judgment for the stimuli presented two times].

Table 1

Results of contrast analyses and corresponding effect sizes (Hedges's *g*) for high and low cognitive load, as well as the difference between these two conditions, in Experiment 1. (For all repeated-measures contrast analyses, *df* = 47, and for the between-group analyses, *df* = 94, *p* values are one sided.)

	Contrast for high CL			Contrast for low CL			Difference		
	t	*p*	*g*	*t*	*p*	*g*	*t*	*p*	*g*
Sensitivity to frequency	28.7	.000	4.14	19.6	.000	2.83	2.38	.010	0.49
Sensitivity to duration	4.52	.000	0.65	4.19	.000	0.60	0.13	.448	0.03
Impact of frequency on duration	2.69	.005	0.39	4.61	.000	0.67	−0.71	.239	−0.15
Impact of duration on frequency	2.38	.010	0.34	3.94	.000	0.57	−1.48	.072	−0.30

Note: CL = cognitive load

Sensitivity to stimulus duration. Contrary to our hypothesis, the relative differences between duration judgments for stimuli presented on different actual duration levels showed a good fit with the predictions for both cognitive-load conditions (see Table 1). As already evident in the values for high and low cognitive load, we did not find a difference between the two cognitive-load conditions concerning the magnitude of sensitivity to stimulus duration (see Table 1, Difference). Although duration sensitivity is not as high as the sensitivity to stimulus frequency, participants were clearly able to differentiate between the different levels of stimulus duration in both experimental conditions.

Influence of stimulus frequency on duration judgments. We had hypothesized that under high cognitive load, the impact of frequency on duration should be high and under low cognitive load it should be low. If at all, we obtained the opposite result (see Table 1). But the between-groups comparison shows that, due to differences in variance in the two groups, there is not much of a difference between the two load conditions (Table 1, Difference). Thus, results indicate that duration judgments were systematically biased by stimulus frequencies in both conditions.

Influence of stimulus duration on frequency judgments. The impact of duration on frequency judgments should be, according to our predictions, stronger in the condition with low cognitive load. Table 1 shows that our results are consistent with this prediction although the size of the effect is not very large (see Table 1, Difference). To summarize, participants were well able to estimate the frequency of the presented stimuli, but presentation duration had a systematic biasing influence on frequency judgments, especially when low cognitive load was induced.

Discussion

We had expected different patterns of results depending on whether participants' cognitive load was high or low: Cognitive load should not make much of a difference for frequency judgments but judgments of duration should follow the actual durations better with low load than with high. The effects for frequency estimates were huge in both conditions, showing an excellent sensitivity to the differences between actual frequencies, but the sensitivity to duration was also quite good in both conditions. Apparently, even in the high cognitive load condition, participants could manage the amount of cognitive load very well. Indeed, the cognitive load we induced in the high cognitive load condition was less than that in prior studies. For instance, Hintzman (1970) used 84 words (instead of 36 in our high cognitive load condition), and although Betsch et al. (2009) also used 36 words, they had participants judge their total presentation durations. Thus, it might not be surprising that in the two conditions, we obtained symmetrical results: Judgments of duration were influenced about equally strongly by actual frequencies as judgments of frequency were by actual durations. There was, however, a slight tendency for the impact of duration on frequency judgments to be stronger in the low cognitive load condition.

In Experiment 1, participants had to make judgments about the frequency and the duration of a single stimulus. As argued above, judgments of total presentation duration are more difficult to generate as compared to judgments of single stimulus duration. To judge total duration, it is necessary to integrate the durations of all repetitions of a given stimulus. The second experiment examines whether similar results occur in this case.

Experiment 2

In this study, we systematically varied stimulus frequency and *total* presentation duration. Cognitive load was again manipulated by using either 36 stimulus words (in the high cognitive load condition) or 9 stimulus words (in the low cognitive load condition). Again, we expected an asymmetrical result pattern in the high cognitive load condition and a symmetrical result pattern in the condition with low cognitive load.

Method

Participants. Ninety undergraduates (57 female, mean age: 23 years, *SD* = 3.8) from different majors at the University of Erfurt participated in the experiment and were paid €5.

Material and procedure. The same word lists as in Experiment 1 were used. Again, participants were randomly assigned to one of the two between-subjects conditions (42 participants in the condition of high cognitive load and 48 participants in the condition of low cognitive load). The stimuli were repeated either two, four, or eight times and were presented for a total duration of 8, 16, or 24 s. If a stimulus now was in the 4 times/8 s condition, it was shown four times for 2 s each with a total presentation duration of 8 s. Thus, the design was again a mixed factorial design with one between-subjects and two within-subject independent variables: 2 (high vs. low cognitive load) × 3 (presentation frequency) × 3 (stimulus duration). Participants were to judge the repetition frequency of each name and the total duration of its presentation. The same general procedure as in Experiment 1 was followed. The whole procedure lasted for about 20 min.

Results

As in Experiment 1, we calculated contrast analyses to test our hypotheses. For the frequencies of 2, 4, and 8 we used contrast weights of −4, −1, and +5, and for the total durations of 8, 16, and 24 s, the contrast weights were −1, 0, and +1. We will again report Hedges's *g* throughout.

Sensitivity to stimulus frequency. As in Experiment 1, we found a high accuracy for frequency judgments (see Table 2). The results indicate that participants were able to differentiate the repetition frequencies of 9 as well as of 36 stimuli reliably. No difference was found with respect to the accuracy of frequency estimates for high versus low cognitive load (Table 2, Difference). Low frequencies (two repetitions) were again, as in Experiment 1, generally overestimated (with a mean of 3.2), and high frequencies (eight repetitions) were underestimated (with a mean of 6.0). The most accurate frequency judgments again were those for the frequency condition providing four repetitions (with a mean of 4.4).

Table 2

Results of contrast analyses and corresponding effect sizes (Hedges's *g*) for high and low cognitive load, as well as the difference between these two conditions, in Experiment 2. (For the repeated-measures contrast analyses for high cognitive load, *df* = 41, and for low cognitive load, *df* = 47; for the between-groups analyses, *df* = 88, *p* values are one sided).

	Contrast for high CL			Contrast for low CL			Difference		
	t	*p*	*g*	*t*	*p*	*g*	*t*	*p*	*g*
Sensitivity to frequency	27.8	.000	4.29	15.3	.000	2.21	0.98	.166	0.21
Sensitivity to duration	1.80	.039	0.28	5.55	.000	0.82	−2.57	.006	−0.55
Impact of frequency on duration	9.31	.000	1.44	5.16	.000	0.76	2.58	.006	0.55
Impact of duration on frequency	1.51	.069	0.23	1.52	.068	0.22	0.01	.496	0.00

Note: CL = cognitive load

Sensitivity to stimulus duration. Under low cognitive load, as expected, duration estimates clearly increased with increasing total presentation duration. Under high cognitive load, in contrast, there was also some sensitivity to total duration but to a clearly lesser extent (Table 2). Taken together, sensitivity to total presentation duration was quite high, but only when cognitive load was low: The ability to discriminate stimulus duration seems to increase when more attentional resources are available for duration processing.

Influence of stimulus frequency on duration judgments. Judgments of total duration estimates increased with increasing stimulus frequency, in both cognitive-load conditions (Table 2). However, as expected, the impact of frequency on duration judgments was higher in the high cognitive load condition (Table 2, Difference). Overall, results indicate that duration judgments are systematically biased by frequency of stimulus presentation.

Influence of stimulus duration on frequency judgments. There was also a slight effect of actual total duration on frequency judgments, in both conditions (Table 2). This effect, however, seems to have been less pronounced than in Experiment 1.

Discussion

Experiment 2 shows that result patterns differ strongly between high and low cognitive load (as compared to Experiment 1), according to the required mode of duration judgments. Although, again, an impact of frequency on duration occurred in both experimental conditions, this effect was higher when a high cognitive load was induced. Under high load, participants' knowledge about stimulus frequencies seems to have been better than their knowledge about total presentation durations. The former seems to have influenced the participants' duration judgments in a systematic way and to a higher extent than was the case in the low cognitive load condition.

If total duration judgments are required, cognitive load might increase (in both conditions, with 36 as well as 9 presented stimuli), because of the need to construct aggregated duration judgments. Hence, the low cognitive load condition in fact induces higher load compared to the respective condition of Experiment 1 (when single duration judgments were required). In Experiment 2, and in contrast to the findings in Experiment 1, asymmetrical result patterns occurred in both experimental conditions: The impact of frequency on duration judgments was clearly higher than the impact of total duration on frequency judgments in both conditions, under high cognitive load, $g = 1.29$, $t(41) = 8.35$, $p = .000$, as well as under low cognitive load, $g = .60$, $t(47) = 4.16$, $p = .000$.

The results in Experiments 1 and 2 indicate that the kind of judgment (single vs. total duration) has a strong impact on the amount of cognitive load participants have to cope with. Therefore, it should be illustrative to compare the results of the two experiments.

Comparison of Experiments 1 and 2

Experiments 1 and 2 used different kinds of measures, as far as duration judgments are concerned: that is, judgments of single versus total duration. These measures are not directly comparable unless they are standardized. As we have already *z*-transformed judgments of both frequency and duration, we use these values for the comparison of Experiments 1 and 2. However, to ensure comparability of fit measures (*L* values), the contrast weights also have to be standardized. Again, this poses no problem for the contrast weights for actual frequencies, which were identical in the two analyses, but the contrast weights for duration (−4, −1, and +5) and those for total duration (−1, 0, and +1) differ. Therefore, these weights were *z*-transformed and new *L* values were calculated with the new weights (see Rosenthal et al., 2000, pp. 159–160).

The most revealing comparison is the one between the conditions that are high or low in both measures of cognitive load: the presentation of 9 stimuli with the requirement of single duration judgments (low cognitive load, Experiment 1) and the presentation of 36 stimuli with the requirement of total duration judgments (high cognitive load, Experiment 2). As the sensitivity to frequencies is high in all conditions and we do not have a specific hypothesis on how cognitive load influences this sensitivity, we concentrate on the other three comparisons. We calculated between-groups contrast analyses for these comparisons (equivalent to between-groups *t* tests).

First, we expected sensitivity to duration to be higher under low cognitive load. The comparison of the two extreme groups for cognitive load supports this hypothesis, $g = .35$, $t(88) = 1.64$, $p = .052$. Although this effect is not large, there is a difference in the sensitivity to duration as hypothesized. Because duration judgments require more attentional resources than frequency judgments, cognitive load is a decisive factor in the accuracy of duration estimates. Under high cognitive load, duration judgments are less accurate compared to a condition where lower cognitive load is induced.

For the influence of frequency on duration, we expected a stronger effect for the high cognitive load condition compared to the low cognitive load condition. This hypothesis was supported by the calculated analysis, $g = -.61$, $t(88) = -2.85$, $p = .003$. It seems that participants oriented their duration estimates to stimulus frequency in situations when sensitivity to duration was low. In fact, this may be an effective strategy for total duration estimates in most cases, because the integral of the single presentation durations of each stimulus repetition has to be generated.

The influence of duration on frequency is the most fragile effect in the relationship between frequency and duration. We expected a higher effect in the condition with the lowest cognitive load compared to the high cognitive load condition of Experiment 2. Here, as for sensitivity to duration, we also found a difference as hypothesized, $g = .38$, $t(88) = 1.79$, $p = .038$, between the extreme conditions of cognitive load. Existing sensitivity to duration seems to be one qualification for the effect of duration on frequency.

General Discussion

The general question that motivated the current research was whether judgments of frequency and duration rely at least partially on the same cognitive mechanisms. As already mentioned, there is some evidence from brain research in support of such mechanisms (e.g., Buhusi & Meck, 2005; Walsh, 2003), but behavioral evidence might be even more convincing. What kind of behavioral evidence should one look for? A strong argument for a common memory representation of duration and frequency would be judgmental “biases.” If, for instance, participants are asked for a frequency judgment, the duration of the stimuli encoded should have a systematic impact on their responses: With a constant given frequency, longer stimulus duration should lead to higher frequency judgments. Likewise, judgments of duration should be influenced by stimulus frequency in the same manner.

Whereas results from animal research are consistent with such a hypothesis, the scarce literature to date on studies with human participants who were to produce judgments of both frequency and duration largely contradicts this assumption. Most of the few studies show an asymmetry: Judgments of duration are influenced by frequencies but not vice versa. The research reported here followed one of the possible explanations for this discrepancy in animal research and research on human memory and learning: The tasks used for human participants might have just been too difficult because of a very high cognitive load induced by the type of experimental task. In our two experiments we varied cognitive load by presenting either 36 (high load) or 9 (low load) stimuli. In addition, across studies, we also varied the difficulty of the type of duration judgment asked for: judgments of single durations (low load) and judgments of total durations (high load). Task difficulty should not have an impact on frequency estimates because there is ample evidence that frequency judgments require only a minimum of attention (e.g., Zacks & Hasher, 2002) but the processing of duration seems to require a substantial amount of attentional resources (Dormal et al., 2006). The attentional resources required to encode 36 different stimuli can be expected to be considerably higher than those needed for the encoding of 9 stimuli. Also, making a judgment about the duration of a single stimulus should bind less attention than making the same judgment about an aggregation of stimuli, because for the latter, either participants have to aggregate their stored perceptions of each single presentation duration or they need to retrieve a typical presentation duration and multiply it by their perceived stimulus frequency. The results in our experiments are consistent with these predictions and therefore provide evidence for at least some cognitive mechanisms common to both frequency and duration judgments.

As already mentioned, a high mutual influence of duration and frequency has also been found for meaningful stimuli, that is, stimuli that arguably were more exciting than names (Betsch et al., 2009; Winkler & Sedlmeier, 2009). Why were the results similar in these two cases? We argue that the amount of symmetry depends on the amount of attention that is directed toward stimuli. In the case of high cognitive load, attention for single stimuli automatically diminishes, especially if the stimuli are not that interesting, whereas meaningful stimuli may draw additional attentional resources. Cognitively controlled time estimates seem to be performed in cortical regions that fulfil attentional requirements (Lewis & Miall, 2003), and the important role of attention in judgments of duration has already been recognized and implemented in prominent models such as the attentional-gate model of time estimation (Zakay & Block, 1997). However, this and similar models are only meant to explain prospective time estimates, that is, time estimates for which participants know in advance that they will have to focus on stimulus duration (see Zakay & Block, 1997). This was very likely not the case in our experiments and therefore, our participants' task might be more aptly categorized as a retrospective estimation task. A common explanation for retrospective timing relies heavily on the use of information stored in memory representing the number of contextual changes that occurred during the interval in question (Block, 2003; Zakay & Block, 1997).

It seems, however, very likely that attention also plays a crucial role in retrospective judgments as our results and others mentioned above indicate. Moreover, to explain the current results, it is also necessary to include some assumptions about the processing of frequencies in an explanatory model. This has already been successfully done for models simulating the behavior of rats and other animals in tasks involving food reinforcement (Church & Broadbent, 1990). Whether these models can be expanded to be able to simulate participants' behavior in the types of complex tasks reported here is still an open question.

Another way to arrive at a convincing model that can explain judgments of both frequency and duration for complex tasks might be to start with precise (computational) models that have proven successful in explaining a broad range of frequency estimates. Existing computational models of frequency processing all use feature coding (an event or object is defined by its features) but differ in their memory representations. They use either memories that grow with every newly encoded piece of information (e.g., MINERVA 2 by Hintzman, 1984, 1988; or MINERVA DM by Dougherty, Gettys, & Ogden, 1999) or fixed size memories that react to newly encoded pieces of information by updating the connection strengths between memory features (e.g., PASS by Sedlmeier, 1999, 2002). From a biological perspective, the latter class of models might be preferable (Church & Broadbent, 1990). Sedlmeier and Winkler (2009; Sedlmeier, 2008) recently developed an extension of the PASS model (PASS-T) that might be a promising candidate to cover estimates of both frequency and duration. Two basic assumptions allow for duration judgments in the model. First, PASS-T postulates the existence of a mechanism that can be regarded as a pacemaker – a widespread assumption in models of time estimation (e.g., Rammsayer, 2003; Wearden, 2003; Zakay & Block, 1997). And second, the amount of learning (modification of associative connections) during one time slice – separated by two successive pulses of the pacemaker – covaries with the amount of attention directed toward the stimulus or collection of stimuli to be encoded. This setup allows simulation of judgments of frequency and duration that vary from very asymmetric to rather symmetric ones. If stimuli are only given a short moment of attention, irrespective of their real duration, frequency judgments are still accurate but judgments of duration are not, whereas if stimuli are attended to as long as they last, both kinds of judgments should be quite accurate. Using (at least partially) identical memory contents should lead to bidirectional biases. It remains to be seen how well PASS-T and similar models are able to cover a broad range of judgments about both frequency and time. In any case, the use of flexible computational models is a good way to advance our understanding of how we deal with basic properties of the world such as time and frequency.

3 When Attention improves Timing – The Impact of Intrinsic and Extrinsic Attention on Judgments of Frequency and Duration

When Attention improves Timing

The Impact of Intrinsic and Extrinsic Attention on Judgments of Frequency and Duration

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Keywords: judgment, frequency, duration, attention

Abstract

Judgments of duration are typically influenced by stimulus frequency, while judgments of frequency, in contrast, are quite accurate and independent of stimulus duration. The present data suggest that this asymmetry vanishes when attention toward the stimuli is enhanced. We manipulated participants' attention (1) in an intrinsic way – by varying the stimuli´s emotional relevance (i.e., by using either emotional pictures or abstract stimulus words), and (2) in an extrinsic way – by varying the physical effort expended during the stimulus presentation (i.e., by requiring the participants to either lift a dumb bell or to rest the arm for the duration of certain stimulus presentation). Participants processed stimuli with varying presentation frequencies and durations, and estimated stimulus frequency and duration subsequently. Sensitivity to duration was increased for emotionally relevant stimuli and for stimuli processed under physical effort. While an effect of stimulus frequency on duration judgments is obtained for all experimental conditions, an effect of presentation duration on frequency judgments, however, only emerged in the condition with pictures and high physical effort. Results are discussed with respect to mechanisms underlying the simultaneous processing of frequency and duration.

For Santiago, the shepherd in Paulo Coelho´s novel “The Alchemist” (1988), it took just a few seconds – as the sheep passed the gate to the field one by one at the daybreak – to notice that one sheep of his little herd was missing, before he went to find it. Also the neurosurgeon Henry Perowne, Ian McEwan´s protagonist of “Saturday” (2005), knows his craft: He knew exactly that he still had seven seconds to arrest the cerebral hemorrhage; otherwise the patient would suffer permanent brain damages. When it matters, people are remarkably sensitive to differences in stimulus frequency or number and stimulus duration (Cordes, Williams, & Meck, 2007; Dormal, Seron, & Pesenti, 2006; Gallistel, 1990). Also the human ability for estimating event frequency (Fiedler, 2002; Whalen, Gallistel, & Gelman, 1999; Williams & Durso, 1986) and stimulus duration (Gallistel, 1996; Meck, 2003; Zakay & Block, 1996) is amazingly good. However, can we trust in our perception of frequency and duration by all means? Or might there be situations in which our judgments tend to be biased, and if so, to which extent? To answer these questions, we need to understand the underlying mechanisms of frequency and duration processing, and the requirements of reliable frequency and duration judgments.

With respect to frequency judgments, especially for small numbers (below ten), even young children and animals are able to detect differences in frequency (see the concept of subitizing by Gallistel & Gelman, 1991; Gallistel, 1989). Hasher and Zacks (1979, 1984) propose that frequency processing is an automatic encoding process, that is, people are able to make accurate frequency estimates without intentional counting (see also Zacks & Hasher, 2002). Frequency judgments therefore should need only minimal attentional resources. Even under difficult circumstances, like stress, high arousal or simultaneous processing demands, frequency estimates remain intact and relatively robust against biases (Hasher & Zacks, 1984). We also know, however, that the accuracy of frequency judgment is improved by deeper levels of processing, associated with higher amounts of attention directed toward the stimuli (Fisk & Schneider, 1984; Greene, 1984, 1986; Johnson, Peterson, Chua Yap, & Rose, 1989; Jonides & Naveh-Benjamin, 1987). Finally, Sedlmeier and Renkewitz (2009) found an unexpected relationship between attention and frequency judgments: The more attention participants direct toward the stimuli during encoding, the higher their frequency estimations tend to be, with a bias toward an overestimation of stimulus frequencies. Overall, the sensitivity to frequency seems to be a stable characteristic of human perception, although any factor that affects the amount of attention directed toward the stimuli has an effect on the corresponding frequency estimates (for an overview, see Sedlmeier and Betsch, 2002).

Let us now briefly consider judgments of duration: Humans, like most animals, have a highly developed sensitivity to duration, and their duration estimates are surprisingly accurate (Gallistel, 1996; Meck, 2003; for an overview on human time perception, see also Helfrich, 2003). However, despite an apparent sensitivity to temporal information across a wide range of intervals (from millisecond to circadian timing, e.g., Buhusi & Meck, 2005), the accuracy of duration judgments differs. Sensitivity to very brief durations (below 500 ms) appears to be extremely high and based on processes that are automatic (Rammsayer, 2003). This kind of duration processing, therefore, needs just low attentional resources (Buhusi & Meck, 2005). The ability to make time judgments for periods of some seconds or minutes, however, seems to be highly dependent of attentional processes (Block, 2003; Buhusi & Meck, 2005; Dormal et al., 2006). Thus, Lewis and Miall (2003, 2006) proposed two different time measurement systems (automatic versus cognitively controlled timing) based on two distinct neural systems. According to this model, the timing of seconds or minutes requires attention, and therefore duration perception is a function of the amount of attention directed toward the temporal information. Due to the fact that attentional resources are limited in our cognitive system, temporal and non-temporal information of a task compete for these attentional resources (Hicks, Miller & Kinsbourne, 1976; Khan, Sharma & Dixit, 2006). If attention is distracted from time-relevant information, duration judgments are characterized by shorter duration estimates and lower accuracy (Brown, 1997; Brown & Boltz, 2002).

Amazing similarities in human (as well as in animal) behavioral functions concerning numerical and temporal processing (Brannon & Roitman, 2003; Church & Broadbent, 1990; Dormal et al., 2006; Fetterman, 1993; Meck & Church, 1983; Meck, Church, & Gibbon, 1985; Roitman, Brannon, Andrews, & Platt, 2007) suggest a common magnitude system for the perception of frequency and duration (Cordes et al., 2007; Walsh, 2003). Although there are differences in the amount of attention required for the processing of both types of information, a common neural basis of frequency and duration processing has been identified (Buhusi & Meck, 2005; Walsh & Pascual-Leone, 2003).

Given that there are common mechanisms for the processing of frequency and duration within the brain – does this imply that these kinds of judgment influence each other mutually? In a pioneer study, Hintzman (1970, Experiment 3) investigated the mutual influence of frequency and duration processing by varying both stimulus frequency as well as presentation duration for three-letter words. The frequency and duration estimates revealed an asymmetrical result pattern: Frequency judgments were quite accurate and only marginally influenced by the presentation duration of the stimuli. Duration judgments, however, were not remotely as accurate and strongly affected by stimulus frequency. This asymmetrical effect was replicated in later studies (Betsch, Glauer, Renkewitz, Winkler, & Sedlmeier, 2009, Experiments 1 and 2; Hintzman, 2004; Hintzman, Summers, & Block, 1975).

The asymmetrical relationship makes perfect sense when considering our knowledge about the attentional demands of frequency and duration processing. Frequency estimation, as already mentioned, is a relatively automatic process (e.g., Hasher and Zacks, 1979), and therefore requires only minimal attentional resources. Judgments should be comparatively reliable (that is, not or not strongly biased by the presentation duration) even when a large number of stimuli is presented or when the stimuli are not in the focus of participants' attention. Duration estimation, however, needs more attentional resources. If these resources are already exhausted (e.g., by a large number of stimuli), duration judgments should be less accurate and – if processed together with stimulus frequency – biased by the more stable frequency judgments.

Winkler, Sedlmeier, Renkewitz, Glauer, and Betsch (2009) demonstrated that cognitive load indeed has a strong impact on frequency and duration judgments. Under high cognitive load, induced by a large number of stimuli and a complex judgment task, an asymmetrical relation between frequency and duration was obtained. Under low cognitive load, however, a more symmetrical relationship was found: Participants revealed a high sensitivity to stimulus frequency as well as to stimulus duration. Furthermore, frequency and duration influenced each other mutually: Duration estimates were influenced by stimulus frequency, and frequency judgments were affected (although weaker but still considerably) by presentation duration of the stimuli. To summarize, when sufficient attentional resources are available for the stimulus processing participants' frequency as well as duration judgments are more accurate. Moreover, presumably due to the same underlying processing mechanism of frequency and duration a more symmetrical result pattern of the judgments with a mutual influence between the two variables is more likely to occur.

In this paper, we examine the effect of attention direction on frequency and duration judgments in order to draw conclusions about the underlying mechanisms of frequency and duration processing. The present study is based on two assumptions: First, as compared to frequency processing, a higher amount of attention is required in order to produce accurate duration judgments (Dormal et al., 2006). Second, while the duration of attention toward the stimuli is irrelevant for judging their frequencies, duration judgments require that the subject attends to the stimuli for their entire presentation duration. We assume that only when stimulus frequency and duration are sufficiently encoded, frequency and duration judgments can influence each other mutually, which would hint at a common processing mechanism of frequency and duration.

For this purpose, we direct our participants' attention toward the stimuli: First, in an intrinsic way, by varying the emotional relevance of the stimuli (either emotional pictures or abstract words). Due to the fact that pictures generally provide more details as compared to words, this stimulus type absorbs more attention. In addition, we use pictures with emotional content, having a higher relevance to the participants, and thus absorbing a higher amount of attention. Second, we direct the participant's attention toward the stimuli in an extrinsic way, by varying the requirement of the physical effort during the stimulus presentation. Hence, we require participants to lift a dumb bell when – and as long as – watching a certain category of stimulus, versus to rest the arm while watching another category of stimulus. To conform to the exercise instruction, participants have to notice both the onset as well as the offset of the respective stimuli. Thus, we want to ensure that the participants would attend to the stimulus for the complete presentation duration and therefore encode the stimulus duration entirely.

We assume that both emotional relevance of the stimuli and physical effort moderate the perception of stimulus frequency and duration. The strongest effect is expected for emotionally relevant stimuli processed under physical exercise conditions. The influence of the amount of attention directed toward the stimuli on the sensitivity to frequency should be quite small, whereas sensitivity to stimulus duration should be strongly enhanced by attentional focusing. Furthermore, we hypothesize an asymmetrical influence of frequency on duration judgments with only marginal effects of duration on frequency estimates when attention is not especially directed toward the stimuli. However, under conditions of higher amounts of attention, we assume a mutual influence between frequency and duration.

Method

Participants. Seventy-five undergraduates (63 female, mean age: 22 years, *SD*=5.5) at the Chemnitz University of Technology participated in the experiment and received course credits for their participation.

Experimental Design. As one independent variable, the emotional relevance of the stimulus material was manipulated between subjects. Participants were presented either stimuli with low emotional relevance (word lists), stimuli with medium emotional relevance (moderately emotional pictures) or stimuli with high emotional relevance (highly emotional pictures). As additional independent variables, we manipulated within subjects the requirement of the physical effort during the stimulus presentation, which either was high (by lifting a dumb bell) or low (by resting the arm), stimulus frequency, and finallystimulus duration. Stimulus frequency was varied by presenting each stimulus either two times, four times, or eight times. Stimulus duration was varied by the total presentation duration of either 16 s, 24 s, or 32 s. Hence, for example, if a stimulus was in the four times/24 s condition, it was presented four times for 6 seconds each.

Material. We used three types of stimuli: (1) 18 different first names, (2) 18 pictures with moderate emotional content, and (3) 18 pictures with high emotional content. The first names were selected from a study by Rudolph, Böhm, and Lummer (2007) providing word norms for a large sample of German first names. From this study, we selected 36 names (see Appendix) with a similar length (two syllables) that scored within the second and third quartile in popularity, and were perceived as being relatively modern. Each participant in the name condition was presented a random sample of 18 first names (9 female and 9 male names). Furthermore, we selected 18 moderately and 18 highly emotional pictures from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 2005). The IAPS is a collection of pictures evaluated for the power of evocating emotions, rated on scales from 1 (low) to 9 (high) for emotional valence as well as intensity of arousal. We selected pictures that evoke positive emotions (valence ratings over 4.5) with either low emotional arousal (arousal ratings below 3.0) or high emotional arousal (arousal ratings over 5.5). Within each experimental condition, we selected 9 pictures illustrating humans (engaged for example in reading or playing chess for low emotional arousal, and in extreme sports or mildly erotic actions for high emotional arousal) and 9 pictures illustrating objects (such as a plant or a boat for low emotional arousal, and a lightning or a rocket for high emotional arousal). The presentation of stimuli and the assessment of dependent measures were controlled by a computer program (E-Prime 2.0 Software, Psychology Software Tools, 2007), run under a Windows XP environment with 17" monitors.

Procedure. Participants were randomly assigned to one of the three between-subjects conditions (first names, moderate emotional pictures, and highly emotional pictures). All participants were tested individually. Upon arrival, they were informed that they now were to watch a series of stimuli (either names or pictures) appearing consecutively on the computer screen, and that they were to answer several questions about these stimuli subsequently. No hint was given that participants would be asked to generate frequency and duration judgments.

For the name condition, the program randomly selected 18 first names from the base list, consisting of 36 names, to build a stimulus sample for each individual session. Male and female names appeared equally often, and no name appeared twice consecutively. We ensured encoding of the stimuli by requiring the participants to read each stimulus word aloud (Johnson et al., 1989). To foster commitment to this instruction, we installed microphones in the cubicles and informed participants that their utterances would be recorded. For the picture condition, a randomized presentation order of the stimuli was created for each individual session. Pictures showing either humans or objects appeared equally often within one stimulus sample, and no picture appeared twice consecutively.

Participants' physical effort during the stimulus presentation was varied by having them to either lift a dumb bell (5 pounds for women, 10 pounds for men) each time when – and as long as –watching a stimulus of a certain category, or to just rest the arm when watching a stimulus of another category.

Within the names condition, the two stimulus categories were female and male names. Within the pictures condition the categories were “pictures showing humans” and “pictures showing objects”. Conditions were completely counterbalanced within participants. To foster participants’ commitment to the appropriate accomplishment of the exercise task, we attached electromyogram electrodes at the biceps of the non-dominant arm designated for the exercise, and informed them that their muscle tension would be recorded.

During a training phase, participants familiarized themselves with the presentation format of the stimuli and the dumb bell exercise. This training lasted about 2 minutes and used stimuli not included in the subsequent experimental trials.

After the presentation of stimuli, participants judged the presentation frequency and the total presentation duration of each stimulus. For both judgment tasks, the stimuli were again presented, in random order, on the computer screen. One half of the participants were first asked to estimate the frequency of each stimulus, and then to estimate the respective stimulus durations. The order was reversed for the other half of participants. For both frequency and duration judgments, participants were explicitly informed about the lowest and the highest possible values to prevent extreme judgments. The experiment took about 20 minutes.

Results

Repeated-measures contrast analyses (see Rosenthal, Rosnow, & Rubin, 2000) were calculated to assess (1) the extent to which participants were sensitive to stimulus frequency, (2) the participants’ sensitivity to total presentation duration, (3) the strength of the influence of stimulus frequency on duration judgments, and (4) the strength of the influence of presentation duration on frequency judgments. For this purpose, we assigned a contrast weight (lambda) to each estimated value according to the actual level of stimulus frequency or duration. That is, judgments in the two times/four times/eight times frequency conditions were assigned lambdas of -4, -1, and +5, according to the relative differences between the frequency levels. Judgments in the 16 s/24 s/32 s total duration conditions were consequently assigned the weights of -1, 0, and +1. In order to increase reliability of the measures, we consistently averaged the estimates over the *z*-transformed values of the non-focal variable (per level of that variable). An example shall explain this procedure: When investigating the effect of actual stimulus frequencies on frequency judgments, we *z*-transformed (per participant) all frequency estimates for stimuli that had been presented for 16 s, all that had been presented for 24 s, and all that had been presented for 32 s to control for level effects that were not of interest in this study. After this, we averaged the z-transformed frequency judgments per participant for the respective frequency levels (two, four, and eight times). An appropriate procedure was applied for sensitivity to duration as well as the frequency effect on duration judgments and the duration effect on frequency judgments. Thus, for each analysis, we calculated three aggregated judgment points per participant. In repeated measures contrast analyses, the fit between a hypothesis (conveyed by the contrast weights) and the data for a given participant is expressed in a single value, most commonly an *L* value (Rosenthal et al., 2000, pp. 128–130). In our investigation, the *L* value is calculated as the dot product of the weights for a given hypothesis and the corresponding aggregated judgments.[1] Using these *L* values, we computed contrast analyses to test our hypotheses. As a measure of effect size, Hedges's *g* will be reported (Rosenthal et al., 2000; Sedlmeier & Renkewitz, 2007).

A preliminary analysis showed that the judgments for moderately and highly emotional pictures did not differ. Therefore, we aggregated the results for these two types of stimuli into one category ("pictures"). In what follows, we compare frequency and duration effects for names versus pictures as well as for low versus high physical effort.

Sensitivity to Stimulus Frequency. Figure 1 shows the mean *z*-standardized frequency estimates for each level of actual stimulus frequency, averaged across the three duration levels. Each of the four lines displays one of the four combinations of the stimulus types (names vs. pictures) and the physical effort conditions (low vs. high). Apparently, frequency judgments systematically covary with actual stimulus frequencies within each of the four experimental conditions, resulting in monotonously increasing frequency judgments with increasing stimulus frequencies. The results of the contrast analyses are summarized in Table 1. Large effect sizes in every experimental condition confirm that the participants are highly sensitive to stimulus frequency.

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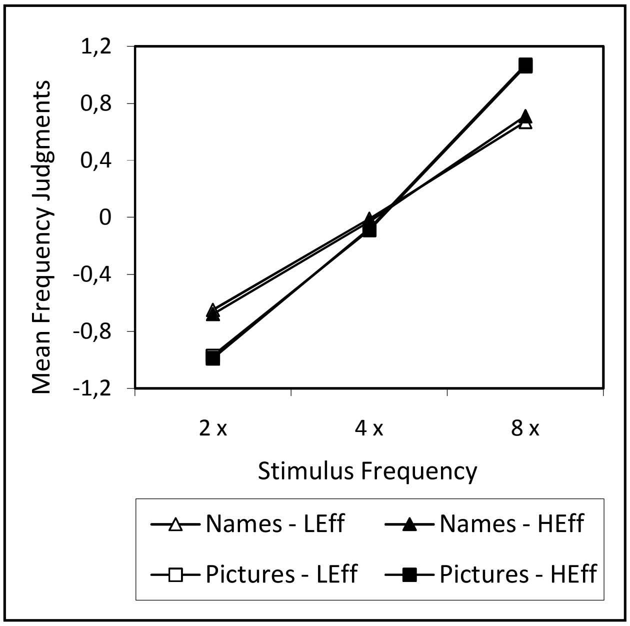
[1] The *L* value for analyzing the sensitivity to presentation frequency, for example, is calculated for each participant by the dot product of the contrast weights (−4, −1, and +5) and the *z*-transformed and aggregated (over the three duration levels) frequency judgments for each level of actual stimulus frequency: $L = -4 \times z(M_{\text{freq2}}) - z(M_{\text{freq4}}) + 5 \times z(M_{\text{freq8}})$ [e.g., $z(M_{\text{freq2}})$ is the aggregated *z*-transformed frequency judgment for the stimuli presented two times].

By means of between-groups contrast analyses (which is – for the comparison of just two groups – identical to a between-groups *t* test) we compared the sensitivity to frequencies between names and pictures, using *L* values for frequency judgments. Differences with a large effect size are obtained for stimulus type, that is, sensitivity to frequency is higher in the picture conditions as compared to the name conditions (see Table 1, Differences Names vs. Pictures). A comparison between the physical effort conditions within a stimulus-type condition was calculated by means of repeated-measures contrast analyses (which is identical to a paired-samples *t* test, as we compare just two measures), again using *L* values for the calculation. The extent of physical effort, however, has no impact on the sensitivity to stimulus frequency (see Table 1, Differences Low vs. High Effort). Despite the high sensitivity to frequencies, the data reveal that low frequencies (two repetitions) are generally overestimated (*M*=3.2), while high frequencies (eight repetitions) are underestimated (*M*=6.2). The most adequate frequency judgments were obtained for the condition providing four repetitions (*M*=4.5). This tendency toward the mean is in line with previous findings on frequency processing (e.g., Fiedler, 1991; Hintzman, 1969; Sedlmeier et al., 1998).

Figure 1

Sensitivity to stimulus frequency (*z*-transformed means)



Note: LEff = Low Physical Effort, HEff = High Physical Effort

Table 1

Results of contrast analyses and corresponding effect sizes (Hedges's *g*) for names and pictures at both high and low physical effort, as well as the difference between the stimulus-type and physical-effort conditions.

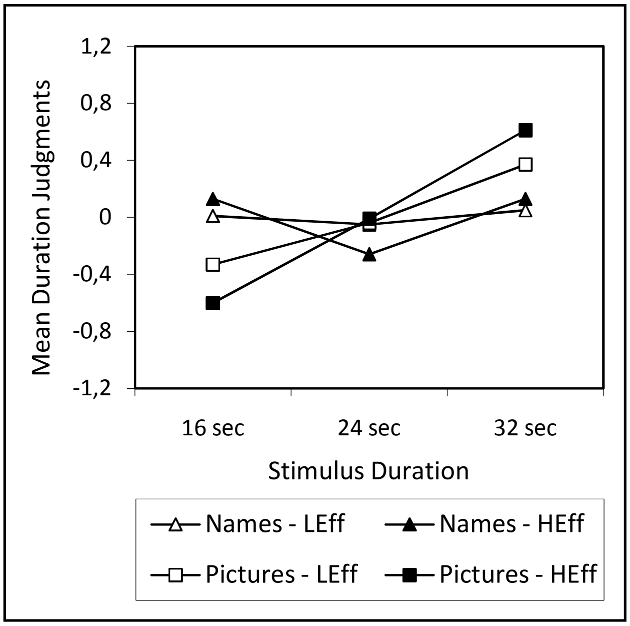
	Names			Pictures			Differences Names vs. Pictures		
	t	*p*	*g*	*t*	*p*	*g*	*t*	*p*	*g*
Low Physical Effort									
Sensitivity to Frequency	7.30	.000	1.46	25.7	.000	3.63	4.29	.000	1.05
Sensitivity to Duration	0.22	.415	0.04	4.37	.000	0.62	2.52	.007	0.62
Influence of Frequency on Duration	3.89	.001	0.78	8.80	.000	1.24	2.18	.017	0.53
Influence of Duration on Frequency	0.30	.383	0.06	1.56	.063	0.22	0.80	.213	0.20
High Physical Effort									
Sensitivity to Frequency	7.74	.000	1.55	32.1	.000	4.54	4.42	.000	1.08
Sensitivity to Duration	0.04	.485	0.01	9.27	.000	1.31	5.20	.000	1.27
Influence of Frequency on Duration	5.15	.000	1.03	12.8	.000	1.81	2.55	.007	0.62
Influence of Duration on Frequency	1.23	.118	0.25	4.80	.000	0.68	1.70	.047	0.42
Differences Low vs. High Effort									
Sensitivity to Frequency	0.28	.393	0.06	0.24	.408	0.03			
Sensitivity to Duration	-0.11	.456	-0.02	2.40	.010	0.34			
Influence of Frequency on Duration	1.00	.165	0.20	1.77	.042	0.25			
Influence of Duration on Frequency	0.76	.228	0.15	2.16	.018	0.31			

Note: For repeated-measures contrast analyses for names, *df*=24, and for pictures, *df*=49; for the between-groups analyses, *df*=73, *p* values are one tailed.

Sensitivity to Stimulus Duration. Figure 2 shows the mean *z*-standardized estimates for total presentation duration, averaged across the three frequency levels. Sensitivity to stimulus duration obviously differs across the experimental conditions. Contrast analyses revealed large effect sizes with respect to duration sensitivity within the picture conditions. Within the name condition, however, participants are not sensitive to differences in stimulus duration (see Table 1). The experimental conditions were compared by use of between-groups *t* tests (between the stimulus-type conditions) and paired-samples t tests (between the physical-effort measures), respectively, revealing differences with large effect sizes between the name and the picture conditions (see Table 1, Differences Names vs. Pictures). In contrast, physical effort has no effect within the name conditions; however, within the pictures condition high physical effort results in a significantly higher sensitivity to duration (see Table 1, Differences Low vs. High Effort).

Figure 2

Sensitivity to stimulus duration (*z*-transformed means)

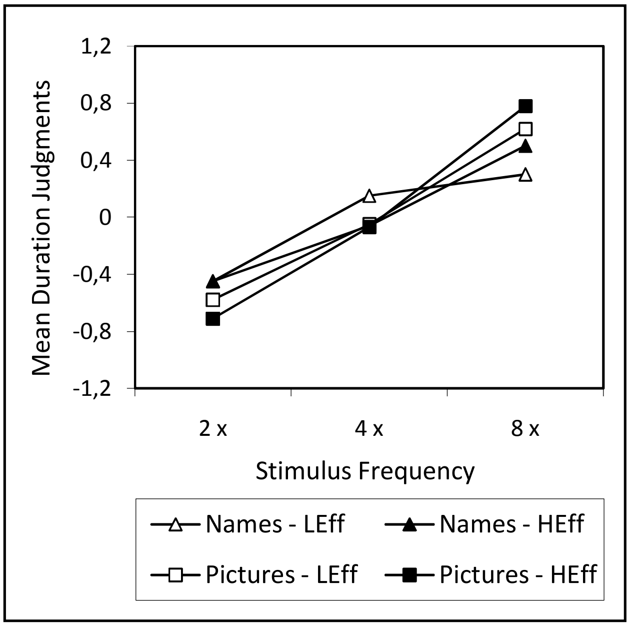


Note: LEff = Low Physical Effort, HEff = High Physical Effort

Influence of Stimulus Frequency on Duration Judgments. Mean *z*-standardized estimates for total presentation duration are displayed in Figure 3, averaged across the three duration levels. Within each experimental condition, we obtain a high covariation between duration estimates and stimulus frequencies. This influence of stimulus frequency on duration judgments is confirmed by large effect sizes for each of the four experimental conditions (see Table 1). The effect is less pronounced in the name conditions (especially for low physical effort), and stronger in the picture conditions (i.e., strongest for high physical effort). Thus, stimulus type strongly influences the frequency effect on duration, supported by large effect sizes for the comparison of the respective *L* values between the name and the picture conditions (see Table 1, Differences Names vs. Pictures). Physical effort operates as an additional (though weaker) moderating variable. The paired-samples *t* tests reveal moderate effects for the comparison of names as well as of pictures with low versus high physical effort (see Table 1, Differences Low vs. High Effort).

Figure 3

Influence of stimulus frequency on duration judgments (*z*-transformed means)

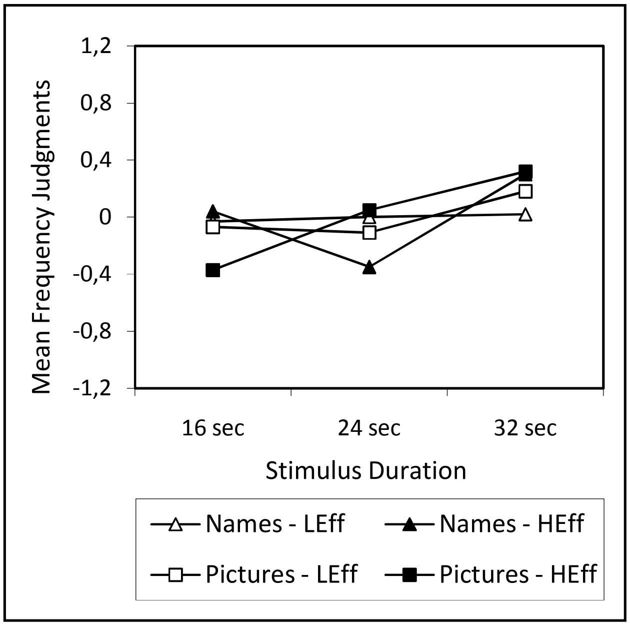


Note: LEff = Low Physical Effort, HEff = High Physical Effort

Influence of Stimulus Duration on Frequency Judgments. Mean *z*-standardized estimates for stimulus frequency are shown in Figure 4, summarizing the differences in covariation of duration judgments with stimulus frequencies for the four experimental conditions. For names processed under low physical effort, a contrast analysis reveals no duration effect on frequency judgments (see Table 1). For names processed under high physical effort as well as for pictures processed under low effort, moderate duration effects are obtained. Furthermore, when both influence factors are combined (within the picture condition linked to high physical effort) a large duration effect on frequency judgments emerges. *T*-tests reveal differences with moderate to large effect sizes for the comparison between the stimulus-type conditions and the physical-effort conditions.

Figure 4

Influence of stimulus duration on frequency judgments (*z*-transformed means)

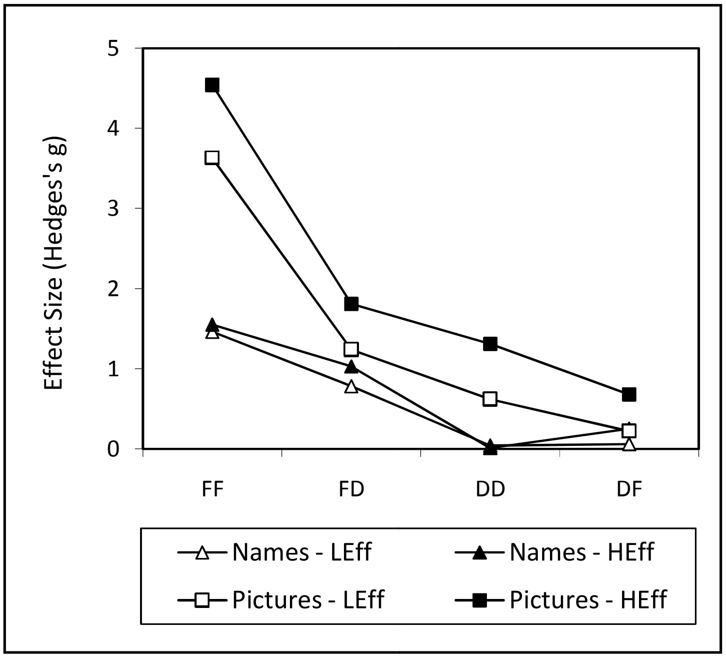


Note: LEff = Low Physical Effort, HEff = High Physical Effort

Summary of Results. Let us briefly summarize the most important findings. Figure 5 gives an overview of the different effect sizes concerning (1) the sensitivity to frequency, (2) the frequency effect on duration judgments, (3) the sensitivity to stimulus duration, and (4) the duration effect on frequency judgments. We find high sensitivity to stimulus frequency in each experimental condition with especially large effect sizes when pictures (instead of names) are presented to the participants. Moreover, the influence of frequency on duration judgments is high in every condition, with larger effect sizes for the pictures conditions as compared to the names conditions. Participants reveal sensitivity to presentation duration when pictures are presented. This sensitivity is even more pronounced when high physical effort is required. For names, however, accurate duration estimates apparently are not possible. A high influence of duration on frequency judgments is obtained only for pictures with high physical effort. By means of the presentation of pictures without physical effort or the induction of physical effort for names, moderate duration effects on frequency judgments are obtained.

Figure 5

Effect sizes (Hedges's *g*) for FF, FD, DD, and DF of the two stimulus types, and the two effort conditions



Note: FF = Sensitivity for Stimulus Frequency, FD = Influence of Stimulus Frequency on Duration Judgments, DD = Sensitivity for Stimulus Duration, DF = Influence of Stimulus Duration on Frequency Judgments, LEff = Low Physical Effort, HEff = High Physical Effort

General Discussion

The general purpose of this study was to test the hypothesis that there is a common mechanism that determines both the processing of frequency and duration as suggested by neuropsychological research (e.g., Walsh, 2003; Walsh & Pascual-Leone, 2003). To date, behavioral studies with human participants did not yield consistent results. In studies simultaneously varying stimulus frequency and duration, typically an asymmetrical relationship between the two variables had been obtained: Frequency judgments are quite accurate and remain basically uninfluenced by stimulus duration. Duration judgments, in contrast, are typically less accurate and are strongly influenced by stimulus frequency.

The results of the present research reveal that the amount of attention directed toward the stimuli during encoding plays a crucial role in the processing of frequency and duration. If sufficient attention is focused on the stimuli, participants are sensitive to both stimulus frequency and presentation duration. This attentional effect seems to be very robust: It does not matter whether attention is generated intrinsically by the special nature of the stimuli (e.g., emotional pictures) or extrinsically by using a specific task (e.g., holding a dumb bell). As a consequence of increased attention, a mutual influence between frequency and duration judgments occurs. As already mentioned, frequency estimation is a relatively automatic process, which requires only minimal attentional resources (Hasher & Zacks, 1984). Therefore, people are quite sensitive to variations in stimulus frequency, even when perceiving a high number of stimuli or when processing personally irrelevant stimuli. The attentional demands of duration estimation, however, are higher. When presenting a large number of stimuli, attentional resources become scarce, and consequently, sensitivity to duration decreases (Winkler et al., 2009). In addition, duration sensitivity is enhanced when presenting stimuli that are relevant to the individual, and therefore attract more attention, or when attention is extrinsically directed toward the stimuli. It is only in this case that people focus their attention toward the stimuli as long as they are presented; as a consequence, differences in presentation duration are perceived more accurately. And only when the perception of both, frequency and duration, is relatively accurate both judgments influence each other.

In the current study, we varied, (1) the emotional relevance of the stimuli, and thereby the amount of attention directed intrinsically toward the stimuli, and (2) the duration of the attention extrinsically directed toward the stimuli by means of a straining physical task. Both, intrinsic and extrinsic attention direction affected the mutual influence between frequency and duration. The strongest mutual influence between frequency and duration, however, occurred when both factors – personal relevance and physical effort – were combined, due to an overall higher amount of attention toward the stimuli.

The presentation of moderately versus highly emotional stimuli did not cause any difference in the result pattern. An explanation could be that these two stimulus groups did not sufficiently differ in their emotionality. Note that we chose exclusively pictures that received positive emotional valence ratings to avoid straining the participants with cruel or disgusting pictures. Generally, the arousal ratings for negative emotional pictures are higher compared to positive emotional pictures in the IAPS. Further research is needed to develop appropriate methods to direct attention toward the stimuli and to analyze the effect of this attention on the simultaneous processing of frequency and duration.

Taken together, the present findings strongly argue for the existence of a common mechanism underlying the processing of frequency and duration. We conclude that stimulus duration is processed entirely given that sufficient attention is directed toward the stimuli, and it is only in this case that a mutual interdependence between frequency and duration appears.

These findings have two implications: First, to estimate the duration of an event accurately, it is – in comparison to frequency estimation – necessary to strongly focus on that event. For Henry Perowne, the neurosurgeon in our initial example, it should be easy to judge the duration of the single steps of a surgery, as the perception of the elapsing time is extremely significant for its success, and he will probably strongly focus on each surgical procedure. However, in daily life situations with simultaneous processing demands, e.g., in traffic situations, our duration judgments might be comparatively less accurate. Second, due to common processing mechanisms, our duration judgments might be biased by the frequency of events occurring in this time span, for example the number of red traffic lights on the way to work.

The development of an explanatory model that integrates both frequency and duration processing, and which is able to simulate frequency and duration judgments accurately, would facilitate a better understanding of how frequency and duration are processed in the human mind. Within animal research such a model already exist (see Meck and Church, 1983), however, it is still unclear whether this model account for human memory processes as well. Recently, Sedlmeier and Winkler (2009; Sedlmeier, 2008) developed a model that integrates both frequency and duration processing. PASS-T is an extension of the PASS model (Sedlmeier, 1999, 2002), an associative learning model that defines events or objects by their features. PASS-T assumes the existence of a pacemaker (Matell & Meck, 2000; Rammsayer, 2003; Zakay & Block, 1997) and it encodes events or objects in discrete time steps provided by the pacemaker. In each time step, the amount of attention directed towards a stimulus is modeled by the (varying) strength of a learning parameter. If, for example, an uninteresting stimulus is presented, PASS-T's learning parameter would be high for the first time steps and then rapidly decrease. Consequently, the memory representation resulting for this stimulus would be not very strong and comparable for stimuli of different durations (because PASS-T would not attend to the stimulus after an initial phase). In contrast, an interesting stimulus would be modeled by PASS-T's learning parameter decreasing only very slowly, which would lead to a better representation of duration.

To use models such as PASS-T for simulating and predicting judgments of frequency and duration might be a promising way to understand a basic cognitive process that might play an important role in many of our daily activities.

4 Not merely a Matter of Time – The Effects of Attention Focusing and Shared Attention on the Processing of Frequency and Duration

Not merely a Matter of Time

The Effects of Attention Focusing and Shared Attention on the Processing of Frequency and Duration

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Keywords: judgment, frequency, duration, attention

Abstract

In previous studies on the processing of stimulus frequencies and durations, duration judgments were influenced by stimulus frequencies, and frequency judgments were influenced by stimulus durations. This mutual effect, however, was obtained only under certain conditions. The present study aims to further clarify these conditions, and investigates the hypothesis that the relationship between frequency and duration judgments is moderated by the availability of attentional resources. In Experiment 1, participants were required to observe traffic situations of varying frequencies and durations, either by watching video sequences (attracting much attention, due to the stimuli being in permanent motion) or fixed images of these situations (attracting less attention). Results indicate a mutual influence between frequency and duration judgments when much attention was attracted, while an asymmetrical relationship (duration judgments being influenced by stimulus frequency, but not vice versa) was obtained when less attention was attracted by the stimuli. These result patterns were replicated in Experiment 2, using a dual-task paradigm with varying attentional demands. Results show that the more attention was distracted from the stimuli by the secondary task, the weaker the mutual influence between frequency and duration was. Results are discussed with regard to the underlying mechanisms of frequency and duration processing.

Consider the following questions, and also how good your answers are presumably going to be: How often have you been to the movies last year? How much time – on average – do you spend in your doctor's waiting room before being allowed to see him or her? How many red traffic lights did you pass on your way to work yesterday, and how long have you been waiting in each case, respectively?

Typically, humans are amazingly good in answering these questions about the frequencies and durations of events (Cordes, Williams, & Meck, 2007; Dormal, Seron, & Pesenti, 2006; Gallistel, 1990). Even without intentionally memorizing stimulus frequencies and durations, in most cases we are able to generate relatively accurate judgments. But how do we process these kinds of information? And what are the requirements for a high sensitivity to both stimulus frequencies and stimulus durations?

Despite the generally highly developed human ability in estimating frequencies and durations, experimental results reveal various factors influencing judgments of frequency and duration (Block, 2003; Sedlmeier, Betsch, & Renkewitz, 2002). When examining these factors, we might gain information about the underlying mechanisms of frequency and duration processing. Although extensive research has been conducted within this field, the results are not entirely straightforward, and a comprehensive model that allows including all existing results does not yet exist. Hence, the present research examines some of the factors influencing the processing of frequencies and durations, thus explaining some of the contradictions inherent in previous findings, and providing some first steps toward the development of a comprehensive model of frequency and duration processing.

Frequency judgments

The perception of stimulus frequencies is an important human ability, enabling us to react and decide adequately within our empirical world (Fiedler, 2002). Frequency processing is a relatively automatic process requiring only minimal cognitive capacities and few attentional resources (Hasher & Zacks, 1979, 1984). In addition, our frequency judgments are (at least typically) remarkably good, even without intentionally counting and even in the presence of additional simultaneous processing demands (Gallistel & Gelman, 1991, Zacks & Hasher, 2002). However, there are several factors involved with respect to frequency processing that influence the quality of frequency estimates (Sedlmeier et al., 2002).

One important factor influencing frequency judgments is the attention directed toward the stimuli during encoding. Although frequency processing requires only few attentional resources, frequency judgments are improved by deeper levels of processing (Fisk & Schneider, 1984; Greene, 1984, 1986;

Jonides & Naveh-Benjamin, 1987). For example, Johnson, Peterson, Chua Yap, & Rose (1989), by using an orienting task, manipulated the amount of attention participants directed toward the stimuli at the encoding stage. The most accurate frequency judgments were obtained within the condition requiring the highest degree of attention.

Another factor influencing frequency judgments is the presentation duration of the respective stimulus. Within a series of studies, exposure duration of several stimuli was varied, and the effect on frequency judgments was examined (Lewandowsky & Smith, 1983; Williams & Durso, 1986). Results show that frequency judgments were systematically biased by presentation durations – longer stimulus durations resulted in higher frequency judgments, even when actual frequencies were in fact held constant. Similar findings were obtained within animal research (Fetterman, 1993; Meck, Church, & Gibbon, 1985). Furthermore, there are several other factors influencing frequency judgments, depending on the context in which the stimuli are presented. Sedlmeier and Betsch (2002) provide a comprehensive overview on the various characteristics of frequency processing.

Duration judgments

Similar to the human ability of estimating frequencies, humans have a highly developed sensitivity to stimulus durations and the ability of producing accurate duration judgments (Buhusi & Meck, 2005; Gallistel, 1996; Rammsayer, 2003). To be able to discriminate between the durations of events is an important skill which may help us organize our daily life, and to make appropriate decisions – sometimes we may save time (e.g., when deciding for situations involving briefer waiting times) or maybe even save somebody's life (e.g., when diagnosing a disease by means of the duration of its symptoms). Humans are able to estimate durations relatively precisely across a wide range of intervals, that is, from milliseconds to hours or days (e.g., Buhusi & Meck, 2005). However, the attentional demands of these kinds of duration judgments differ. Judgments of very brief durations (below 500 ms) are based on automatic processes (Rammsayer, 2003). The processing of durations within seconds or minutes requires more attentional resources (Lewis and Miall, 2003, 2006). As in the case of frequency judgments, there are several factors that affect duration judgments.

One important factor influencing duration judgments is the amount of attention directed toward the stimuli during encoding. In the case of duration processing, it is not only the intensity of attention that exerts an influence, but its (uninterrupted) presence as well. In order to be able to sufficiently process a stimulus' duration, attention toward this stimulus has to sustain for its complete duration (Brown, 1997; Khan, Sharma, & Dixit, 2006; Rammsayer, 2003). If attention is distracted from the stimuli, duration judgments tend to be shorter and less accurate (Brown, 1997; Brown & Boltz, 2002; Khan et al., 2006).

Another factor influencing duration judgments is the frequency of the stimuli under consideration. In almost every study on the impact of stimulus frequency on duration estimates, we find durations perceived as being longer when stimulus frequencies increase, even when presentation duration is in fact held constant (e.g., Block, 2003; Hintzman, 1970; Hintzman, Summers, & Block 1975). Similar findings were obtained within animal research (Fetterman, 1993; Meck & Church, 1983).

A variety of additional factors influencing duration judgments exist, belonging to either personal characteristics (e.g., the person's temporary arousal or age; Zakay & Block, 1996, 1997; Block, Zakay, & Hancock, 1999) or situational characteristics (e.g., the complexity of the stimuli; Ornstein, 1969). It is interesting that these factors hardly have an impact on the quality of frequency judgments (Hasher & Zacks, 1984), which demonstrates that frequency judgments are generally less prone to biases as compared to duration judgments.

The interactions of frequency and duration processing

Based on what we know about the factors on the processing of frequency and duration, two conclusions can be drawn: (1) Stimulus frequency and presentation duration influence each other mutually, at least under certain conditions. (2) Both judgments of frequency and duration are more accurate when attention to the respective stimuli is increased. This leads to the assumption that one common mechanism is underlying the processing of frequency and duration. Actually, various findings exist that argue for a common process explanation, suggesting a common magnitude-representation system of the perception of frequencies and durations (Dormal et al., 2006; Walsh, 2003; Walsh & Pascual-Leone, 2003). In addition, neuropsychological research supports this assumption (Cordes et al., 2007), as a common neural basis has been identified (the thalamo-cortico-stratial circuits) that is shared by both frequency and duration processing (Buhusi & Meck, 2005).

However, as already mentioned, conflicting results have been obtained within human behavioral research, challenging the assumption of a common processing mechanism. For example, Hintzman (1970) simultaneously varied stimulus frequencies and durations for a large number of words, allowing for an analysis of the interaction between frequency and duration processing. An asymmetrical result pattern for judgments of frequency and duration was an unexpected but reproducible finding: Frequency judgments were relatively accurate and uninfluenced by presentation durations. However, duration judgments were not as accurate and strongly influenced by stimulus frequencies. This asymmetrical effect was replicated in later studies (Betsch, Glauer, Renkewitz, Winkler, & Sedlmeier, 2009; Hintzman, 2004; Hintzman et al., 1975).

In the present article, we assume that the obtained asymmetrical relationship between frequency and duration is in fact a research artifact. In our view, this is because the processing of frequencies and durations requires different degrees of attentional resources. The processing of frequency requires only few attentional resources (Hasher & Zacks, 1984), in fact just for the moment of stimulus onset. However, duration processing requires more attention, which has to remain present for the complete presentation duration of the stimulus (Block, 2003). If the attentional resources are exhausted, due to the presentation of a large number of stimuli (as in the experiment of Hintzman, 1970), or if participants focus their attention just briefly on the stimuli, due to the presentation of relatively simple stimuli without any personal relevance, stimulus durations cannot be encoded adequately. As a consequence, frequency judgments can be relatively accurate even in the presence of limited attentional resources, while duration judgments might be less accurate. Based on the assumption that stimulus frequencies and durations are processed together, the undifferentiated duration perceptions would be influenced by the sensitive frequency judgments (which differ with respect to the actual stimulus frequencies). However, because duration judgments would hardly differ based on the actual stimulus durations, frequency judgments would remain uninfluenced by duration judgments.

Winkler, Sedlmeier, Renkewitz, Glauer, and Betsch (2009) demonstrated that cognitive load – associated with high versus low attentional resources for stimulus processing – has a strong impact on frequency and duration judgments. Under high cognitive load, induced by a large number of stimuli and a complex judgment task, an asymmetrical relationship between frequency and duration was obtained. Under low cognitive load, however, a more symmetrical relationship was found: Participants revealed a high sensitivity to stimulus frequencies as well as to stimulus durations. Furthermore, frequency and duration influenced each other mutually.

In addition, Winkler and Sedlmeier (2009) directed attention toward the stimuli either by presenting emotionally relevant stimuli or by employing a task requiring the direction of attention toward the stimuli for the complete stimulus duration. The results showed that the highest sensitivity to both stimulus frequencies and durations was obtained when emotionally relevant stimuli were presented plus additional attention was directed toward the stimuli by the task. In this condition, a mutual influence between frequency and duration occurred. However, when no attention was directed toward the stimuli an asymmetrical result pattern was replicated.

Due to the fact that the previous studies used relatively artificial contexts, it was one aim of the present research to analyze frequency and duration judgments within more realistic settings to increase the external validity of our results. In this paper, we investigate attention as a factor influencing frequency and duration processing in order to draw conclusions about the mechanisms of frequency and duration processing. We assume that when sufficient attention is directed toward the stimuli, then stimulus frequencies and presentation durations are both encoded completely. As a consequence, participants are able to perceive differences in both stimulus frequencies and durations. Furthermore, given that stimulus frequencies and durations are completely encoded, we expect a mutual influence between frequency and duration judgments. In the case of one common mechanism underlying the processing of frequencies and durations, duration judgments would be influenced by stimulus frequencies and, in a similar way, frequency judgments would be influenced by presentation durations.

In contrast, under less ideal conditions (i.e., the stimuli are not in the focus of participant's attention or attention is distracted from the stimuli), we expect a decrease in sensitivity to stimulus durations; however, due to the lower attentional demands of frequency processing, the sensitivity to stimulus frequencies is assumed to remain quite high. Furthermore, in situations with low attentional resources, we expect an asymmetrical relationship between frequency and duration judgments: The relatively accurate frequency perceptions are assumed to be not (or only slightly) modified by presentation durations, due to the fact that duration perceptions hardly vary between the actual (different) stimulus durations. In contrast, we assume that duration judgments are strongly influenced by the perceived stimulus frequencies (given that stimulus frequencies and durations are processed together), because frequency perceptions covary strongly with actual stimulus frequencies.

In two experiments, we varied the amount of attention focused on the stimuli. In Experiment 1, we presented stimuli that either attracted much attention due to the presentation of realistic traffic simulations that are in permanent motion, or less attention due to the use of relatively simple and artificial stimuli. In Experiment 2, we varied the amount of attention distracted from the stimuli by varying the nature of a second task within a dual-task paradigm, using a realistic internet setting. For both studies, we expect a higher sensitivity to durations as well as a stronger mutual influence between frequency and duration, when more attentional resources are available for the stimulus processing.

Experiment 1

We systematically varied stimulus frequencies and durations for either video sequences of different traffic situations or fixed images of these situations. The video sequences are supposed to attract participant's attention for the complete stimulus duration, due to the stimuli being in permanent motion. Fixed images, however, are assumed to attract participant's attention only briefly (probably just for the stimulus onset), due to the fact that the stimuli are not changing during their presentation. Sensitivity to stimulus frequencies and presentation durations as well as the strength of the mutual influence between frequency and duration are examined.

Method

Participants. Eighty-five undergraduates (41 female, mean age: 23 years, *SD*=3.7) at the Chemnitz University of Technology participated in the present experiment and either received course credits for their participation or were paid €5.

Material. Participants were presented either 9 different waiting situations within a traffic-simulation video, or 9 fixed images of the same waiting situations. The video was created by means of a traffic-simulation software (STISIM Drive, Systems Technology, 2007), putting the participants into the perspective of a car driver. Participants either drove along a fictitious street, experiencing a number of waiting situations (e.g., traffic lights with crossing traffic or pedestrian crossings), or simply watched pictures of the same waiting situations. Stimulus frequency was varied by repeating each stimulus (either traffic situations or fixed images) either 2, 4, or 6 times. Each single stimulus presentation lasted either 5, 10, or 20 sec. Stimuli were presented in a random order, with the only restriction being that no stimulus appeared twice consecutively. For the picture condition, a randomized presentation order of the stimuli was created for each individual session. For the traffic simulations, three videos varying in the order of the waiting situations were created to avoid any order effects. The presentation of the stimuli and the assessment of dependent measures were controlled by a computer program (E-Prime 2.0 Software, Psychology Software Tools, Inc., 2007) under a Windows XP environment, using 17" monitors.

Procedure. Participants were randomly assigned to either the picture condition (*N*=25) or to one of the three versions of the video condition (*N*=20 for each video). All participants were individually tested in separate cubicles. Upon arrival, they were informed that they now were to watch either a traffic-simulation video or a series of pictures appearing consecutively on the computer screen, and that they were to answer several questions about the presentation subsequently. No hint was given that participants would be asked to generate frequency and duration judgments.

After the presentation of stimuli, participants judged the presentation frequencies and the presentation durations of each stimulus. For both judgment tasks, the stimuli were again presented in random order on the computer screen. One half of the participants were first required to estimate the presentation frequency of each stimulus, and then to estimate the respective stimulus durations.

The order was reversed for the other half of participants. For both frequency and duration judgments, participants were explicitly informed about the lowest and the highest possible values to prevent extreme judgments. The experiment took about 20 minutes.

Results

A preliminary analysis showed that the judgments for the three versions of the traffic-simulation videos (varying in stimulus order) did not differ. Therefore, we aggregated the results for these three between-subjects groups into one stimulus condition ("traffic simulations"). In what follows, we compare frequency and duration judgments for traffic simulations versus fixed images.

In order to examine the judgments of frequency and duration for both kinds of stimuli, we calculated repeated-measures contrast analyses (see Rosenthal, Rosnow, & Rubin, 2000), and we did so separately for each of the two stimulus conditions. Four repeated-measures contrast analyses were conducted to analyze the quality of frequency and duration judgments and their interactions. (1) The participants' sensitivity to stimulus frequencies was measured by the fit between the actual stimulus frequencies and the respective frequency judgments. (2) In a similar vein, the sensitivity to stimulus durations was measured by the fit between the actual stimulus durations and the respective duration judgments. The mutual influence between judgments of frequencies and durations was measured by means of (3) the influence of actual stimulus frequencies on duration judgments, and (4) the influence of actual stimulus durations on frequency judgments.

These contrast analyses are based on standardized procedures: We assigned a contrast weight (lambda) to each estimated value (either frequency or duration judgments) according to the actual level of stimulus frequency or duration. That is, judgments in the 2 times/4 times/6 times frequency conditions were assigned lambdas of -1, 0, and +1, according to the relative differences between the actual frequency levels. Judgments in the 5 sec/10 sec/20 sec duration conditions were assigned the weights of -4, -1, and +5.

To increase the reliability of the measures, we consistently averaged the judgments across the *z*-transformed values of the non-focal variable (for each level of this variable). For example, when examining the fit between the actual stimulus frequencies and the respective frequency judgments, we first *z*-transformed (per participant) all frequency judgments for stimuli that had been presented for 5 sec, all that had been presented for 10 sec, and all that had been presented for 20 sec, in order to relativize the dissimilarities of the judgments between these stimulus groups. Subsequently (and again for each participant) we calculated the average of all *z*-transformed judgments for a given presentation frequency (2 times, 4 times, and 6 times). Another example is the calculation of the influence of stimulus durations on frequency judgments: Here, we performed the *z*-transformation for each level of frequency (instead of each duration level) and averaged frequency judgments across each frequency level. Thus, for each analysis, we calculated three aggregated judgment points per participant.

In repeated-measures contrast analyses, the fit between a hypothesis (conveyed by the contrast weights) and the data for a given participant is expressed by means of a single value, most commonly an *L* value (Rosenthal et al., 2000, pp. 128–130). In our investigation, the *L* value is calculated as the dot product of the weights for a given hypothesis and the corresponding aggregated judgments.[1] Using these *L* values, we computed contrast analyses to test our hypotheses. As a measure of effect sizes, Hedges's *g* will be reported (Rosenthal et al., 2000; Sedlmeier & Renkewitz, 2007).

In order to compare each of the findings between the two stimulus conditions, we compared the *L* values of each of the repeated-measures contrast analyses by means of a between-groups contrast analysis (which in this case with two groups is identical to a between-groups *t* test). In what follows, we report the results of each of the four repeated-measures contrast analyses, and subsequently compare the findings of the two between-subjects stimulus conditions.

Sensitivity to stimulus frequencies. Figure 1 shows the mean *z*-standardized frequency estimates for each level of stimulus frequency, averaged across the three duration levels. The two lines display the frequency judgments for the two stimulus conditions (traffic simulations vs. fixed images). As can be seen from the figure, frequency judgments systematically covary with actual stimulus frequencies in both stimulus conditions, resulting in monotonously increasing frequency judgments across increasing stimulus frequencies. The results of the contrast analyses are summarized in Table 1. Large effect sizes in both stimulus conditions confirm that the participants are highly sensitive to stimulus frequencies. No differences in sensitivity to frequencies are obtained between the two stimulus conditions (Table 1, Difference).

Despite the high sensitivity to stimulus frequencies, low frequencies (two repetitions) are generally overestimated ($M = 2.5$), while high frequencies (six repetitions) are underestimated ($M = 5.1$). The most accurate frequency judgments were obtained for the condition providing four repetitions ($M = 4.0$). This tendency toward the mean is well known in research on frequency processing (Fiedler, 1991; Hintzman, 1969; Sedlmeier, Hertwig, & Gigerenzer, 1998).

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[1] The *L* value of the repeated-measures contrast analysis for analyzing the sensitivity to stimulus duration, for example, is calculated for each participant by the dot product of the contrast weights (−4, −1, and +5) and the *z*-transformed and aggregated (across the three frequency levels) duration judgments for each level of actual stimulus duration: $L = -4 \times z(M_{\text{dur5}}) - z(M_{\text{dur10}}) + 5 \times z(M_{\text{dur20}})$ [e.g., $z(M_{\text{dur5}})$ is the aggregated *z*-transformed duration judgment for the stimuli presented for 5 sec].

Figure 1

Sensitivity to Stimulus Frequency (*z*-transformed means), Experiment 1.

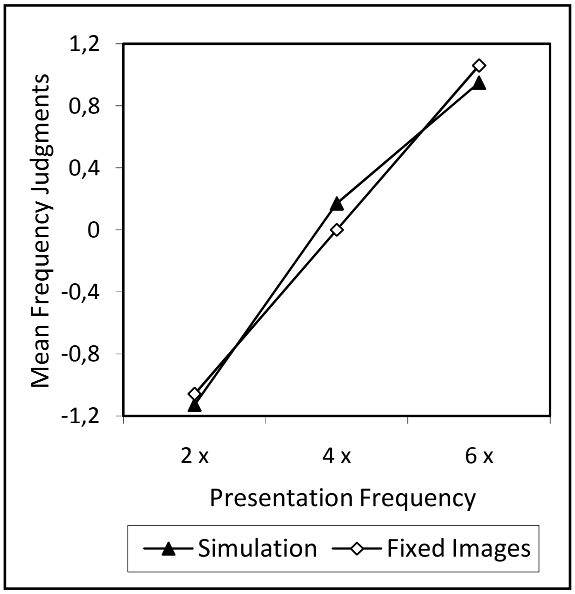


Table 1

Results of contrast analyses and corresponding effect sizes (Hedges' *g*) for traffic simulation and pictures, as well as the difference between these two conditions, in Experiment 1.

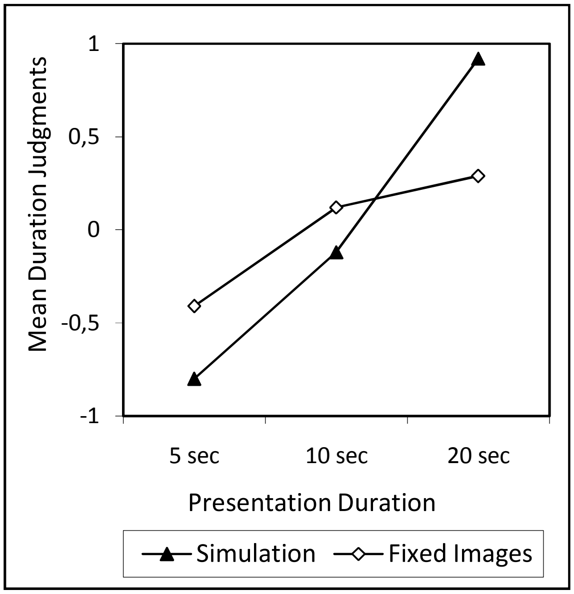
	Traffic Simulation			Fixed Images			Difference		
	t	*p*	*g*	*t*	*p*	*g*	*t*	*p*	*g*
Sensitivity to Frequency	34.8	.000	4.49	37.1	.000	7.42	-0.50	.310	-0.12
Sensitivity to Duration	21.0	.000	2.71	2.55	.009	0.51	5.26	.000	1.25
Influence of Frequency on Duration	1.81	.037	0.23	9.48	.000	1.90	-6.32	.000	-1.50
Influence of Duration on Frequency	4.86	.000	0.63	0.91	.186	0.18	1.88	.032	0.45

Note: For the repeated-measures contrast analyses for the traffic simulation, *df*=59, and for pictures, *df*=24; for the between-groups analyses, *df*=83, *p* values are one sided.

Sensitivity to stimulus durations. Figure 2 shows the mean *z*-standardized duration estimates for each level of stimulus duration, averaged across the three frequency levels. Apparently, sensitivity to stimulus duration differs between the two stimulus conditions. In the traffic-simulation condition, the contrast analysis for sensitivity to durations reveals a large effect size (see Table 1). A lower sensitivity to durations (with a moderate effect size) is obtained when fixed images were presented. Comparing the duration sensitivities by means of a between-groups contrast analysis reveals that the sensitivity to durations in the traffic-simulation condition is substantially higher (Table 1, Difference).

Figure 2

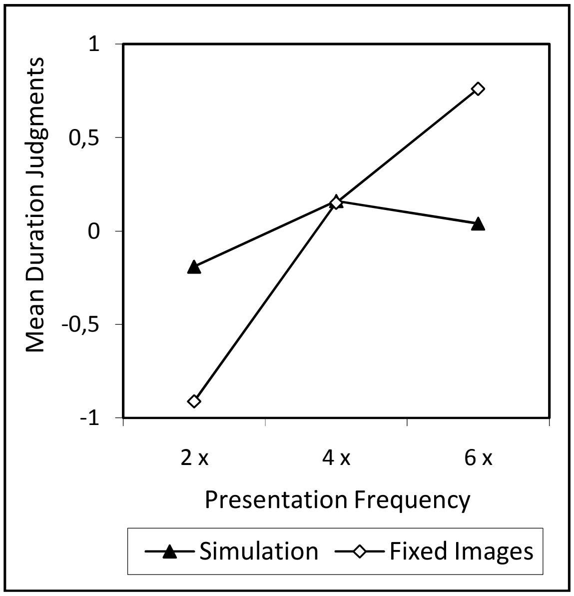
Sensitivity to Stimulus Duration (*z*-transformed means), Experiment 1.



Influence of stimulus frequencies on duration judgments. Mean *z*-standardized duration estimates for each level of stimulus frequency, averaged across the three duration levels are displayed in Figure 3. The influence of stimulus frequencies on duration judgments differs strongly between the two stimulus conditions with a larger frequency effect in the fixed-images condition. This finding is confirmed by corresponding effect sizes (i.e., a low effect size in the traffic-simulation condition and a large effect size in the fixed-images condition; see Table 1). Moreover, the comparison between the stimulus conditions reveals a large effect size (Table 1, Difference).

Figure 3

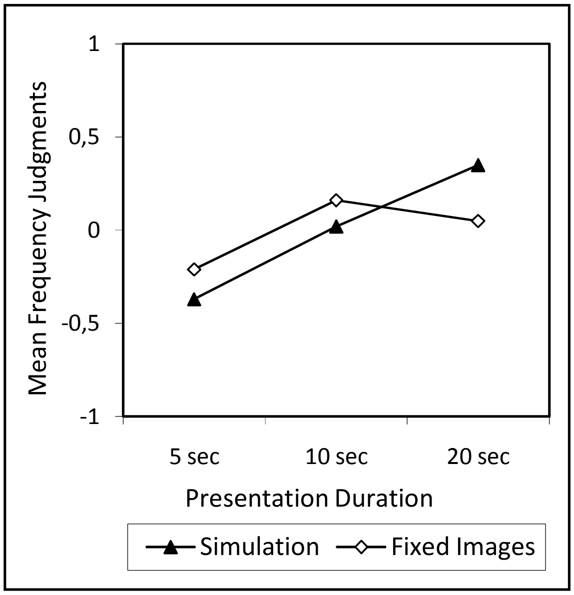
Influence of Stimulus Frequency on Duration Judgments (*z*-transformed means), Experiment 1.



Influence of stimulus durations on frequency judgments. Mean *z*-standardized frequency estimates for each level of stimulus duration, averaged across the three frequency levels are shown in Figure 4, hinting at a difference between the stimulus conditions. In the traffic-simulation condition, a large effect size for the influence of stimulus durations on frequency judgments is obtained (see Table 1). This effect is much smaller in the fixed-image condition. The between-groups contrast analysis confirms this difference by a moderate effect size (Table 1, Difference).

Figure 4

Influence of Stimulus Duration on Frequency Judgments (*z*-transformed means), Experiment 1.



Discussion

We expected different result patterns for frequency and duration judgments depending on the stimulus type. Due to the fact that the traffic simulations provide more realistic stimuli that are in permanent motion, it was assumed that this kind of stimuli attracts more attention for the complete stimulus duration, as compared to the relatively simple and artificially fixed images of the same traffic situations. Because frequency processing requires only few attentional resources (in fact, participants have to direct their attention toward the stimuli only for the stimulus onset), a high sensitivity to frequencies for both kinds of stimuli was expected. The results confirmed this hypothesis by large effect sizes for sensitivity to stimulus frequencies in both stimulus conditions. However, due to the fact that high attentional resources for the complete stimulus durations are required to allow for sufficient duration processing, differences in sensitivity to durations between the two stimulus conditions were expected. As hypothesized, sensitivity to durations was high when traffic simulations were presented. In the fixed-images conditions, in contrast, sensitivity to duration was lower when compared to the condition of the traffic simulations, although yet not generally low.

Furthermore, we expected different interaction patterns between frequency and duration judgments, depending on stimulus types. In the traffic-simulations condition, a mutual influence between frequency and duration judgments was hypothesized, given a high sensitivity to both stimulus frequencies and durations. In previous studies, the critical point within this interaction was the effect of stimulus durations on frequency judgments; this effect was obtained only rarely. The present results reveal a high effect size for the respective contrast analysis. Even though the effect size for the influence of stimulus frequencies on duration judgments was relatively small, a mutual influence between frequency and duration judgments was obtained. In the fixed-images condition, however, we expected an asymmetrical relationship between frequency and duration judgments, with duration judgments being influenced by the highly sensitive frequency perceptions, but not vice versa. The results support this expectation, as a high effect size for the frequency effect on duration judgments is obtained, and a small effect size for the effect of stimulus durations on frequency judgments.

In Experiment 1, attention was directed toward the stimuli by the use of realistic stimuli. As expected, sensitivity to both stimulus frequencies and stimulus durations, as well as a mutual influence between frequency and duration judgments were obtained. However, by the use of artificial and relatively simple stimuli an asymmetrical relationship, as obtained in previous studies, was replicated.

In Experiment 2, we again used a realistic experimental setting, including a method to systematically distract the participants' attention from the stimuli. Thus, the following study aimed to examine the effect of attention on frequency and duration processing by means of a dual-task paradigm.

Experiment 2

In this study we used a dual-task paradigm (simulating a realistic situation in the internet), and varied the amount of attention distracted from the stimuli by the application of different secondary tasks. Again, we varied stimulus frequencies and durations, and examined the sensitivity to stimulus frequencies and durations as well as the mutual influence between frequency and duration judgments.

Method

Participants. Sixty-six undergraduates (41 female, mean age: 21 years, *SD*=3.0) at the Chemnitz University of Technology participated in the present experiment and either received course credits for their participation or were paid €5.

Material. Stimuli were 9 promotional images (referred to as “pop ups” in the internet) showing a picture of the product (e.g., a cell phone by Nokia, or a car by Audi), the name of the product and a line of the commercial. These images were either presented while participants had to accomplish one of two secondary tasks – reading an article or watching a documentary – or without a secondary task (control condition). We varied stimulus frequency and presentation duration of these stimuli within-subjects. Thus, each stimulus was presented either 2, 4, or 6 times with single stimulus durations of either 2, 4, or 6 sec. Stimuli were presented in a random order for each individual session, with the only restriction being that no stimulus appeared twice consecutively. The presentation of stimuli and the assessment of dependent measures were controlled by a computer program (E-Prime 2.0 Software, Psychology Software Tools, Inc., 2007) under a Windows XP environment, using 17" monitors.

Procedure. Participants were randomly assigned to one of three between-subjects conditions (N=22 for each condition): (1) In the article condition, participants were required to read an article about self-perception on the computer screen. They were instructed to read the article carefully to be able to answer some questions about this article later. Furthermore, participants were informed that “pop ups” would appear on the screen covering the article for a given time span. Participants were asked to watch these pop ups carefully to be able to answer some questions about these images later as well. (2) In the video condition, participants were required to watch a documentary about phobias. They were informed that they were to answer some questions about the content of this video afterwards. Furthermore, participants were instructed that “pop ups” would appear on the monitor covering the screen for a given time span without interrupting the sound of the documentary. Thus, participants would still be able to follow the content of the documentary, despite the pop-up presentation. Participants were informed that they would be required to answer some questions about the “pop ups” after the presentation as well. (3) In the control condition, participants were informed that they would watch a series of promotional images appearing consecutively on the screen, and that they were to answer some questions about these stimuli in succession.

All participants were individually tested in separate cubicles. No hint was given that participants would be asked to generate frequency and duration judgments. After the stimulus presentation, participants judged the presentation frequency and the single presentation duration of each “pop up”. For both judgment tasks, the stimuli were again presented, in random order, on the computer screen. One half of the participants were first asked to estimate the frequency of each stimulus, and then to estimate the respective stimulus durations. The order was reversed for the other half of participants. For both frequency and duration judgments, participants were explicitly informed about the actual lowest and the highest values to prevent extreme judgments. Participants were not required to answer question concerning the content of the article or the documentary. The experiment took about 20 minutes.

Results

As in Experiment 1, we calculated repeated-measures contrast analyses in order to examine the judgments of frequency and duration, separately for each of the three experimental conditions (article condition, video condition, and control condition). Again, four analyses were conducted to analyze (1) the sensitivity to stimulus frequencies, (2) the sensitivity to stimulus durations, (3) the influence of stimulus frequencies on duration judgments, and (4) the influence of stimulus durations on frequency judgments. For the calculation of the contrast analyses, we assigned contrast weights of −1, 0, and +1 to the frequency and duration judgments, according to the relative differences between the actual frequency levels (2 times/4 times/6 times) or duration levels (2 sec/4 sec/6 sec), respectively. Again, we averaged the judgments across the z-transformed values of the non-focal variable (for each level of that variable). As a measure of effect size for the repeated-measures contrast analyses, Hedges's g will be reported.

To analyze differences between the three experimental conditions, we calculated between-groups contrast analyses on the basis of the L values for each of the repeated-measures contrast analyses. We hypothesize that the more attention is distracted from the stimuli (the pop ups), (1) the lower the sensitivity for stimulus frequencies, (2) the lower the sensitivity for stimulus durations, (3) the smaller the influence of stimulus frequencies on the duration judgments, and (4) the smaller the influence of stimulus durations on the frequency judgments. Due to the fact that frequency processing requires only few attentional resources, we suppose that the effects of distracted attention are only small for (1) and (3). This is because sensitivity to frequencies will presumably be enhanced only slightly due to higher attentional resources, and thus, in a similar way, the influence of stimulus frequencies on duration judgments will also just slightly increase.

Furthermore, we assume that the highest amount of attention is distracted from the stimuli in the article condition, because participants have to interrupt reading and to memorize the read content during the pop-up presentations. The cognitive resources, therefore, have to be shared between stimulus processing and memorizing the content of the article. However, in the video condition less attention will be distracted from the stimuli, because the participants are still able to follow to the sound of the documentary while pop ups covered the screen from time to time. In the control condition, presumably the largest attentional resources were available for the processing of frequencies and durations. Based on these assumptions, a contrast weight of −1 was assigned to the

L values of the article condition, a weight of 0 was assigned to the *L* values of the video condition, and a weight of +1 was assigned to the *L* values of the control condition in order to compare the results of the four repeated-measures contrast analyses between the three experimental conditions. As a measure of effect size for the between-groups contrast analyses, $r_{\text{effectsize}}$ will be reported (Rosenthal et al., 2000; Sedlmeier & Renkewitz, 2007).

In what follows, we report the results of the repeated-measures contrast analyses, and subsequently compare these findings between the experimental conditions by means a between-groups contrast analysis.

Sensitivity to stimulus frequencies. Figure 5 shows the mean *z*-standardized frequency estimates for each level of actual stimulus frequencies, averaged across the three duration levels. The three lines display the frequency judgments for the three experimental conditions. The results of the contrast analyses are summarized in Table 2. Large effect sizes in all experimental conditions reveal that the participants are highly sensitive to stimulus frequencies. The comparison of the experimental conditions by means of a between-groups contrast analysis supports the hypothesis (the more attention is distracted from the stimuli, the lower the sensitivity to frequencies) by a moderate effect size (Table 2, Comparison).

As in Experiment 1 we also find a tendency toward the mean of the frequency judgments. That is, low frequencies (two repetitions) were generally overestimated (M = 2.8), while high frequencies (six repetitions) were underestimated (M = 4.9). The most accurate frequency judgments were obtained for the condition providing four repetitions (M = 4.1).

Figure 5

Sensitivity to Stimulus Frequency (*z*-transformed means), Experiment 2.

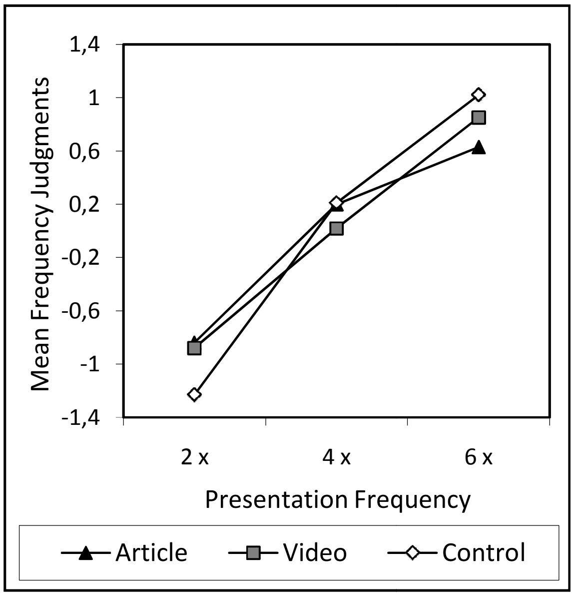


Table 2

Results of contrast analyses for the article condition, the video condition and the control condition, as well as for the comparison between these conditions, and corresponding effect sizes (Hedges' *g* and $r_{effectsize}$, respectively), in Experiment 2.

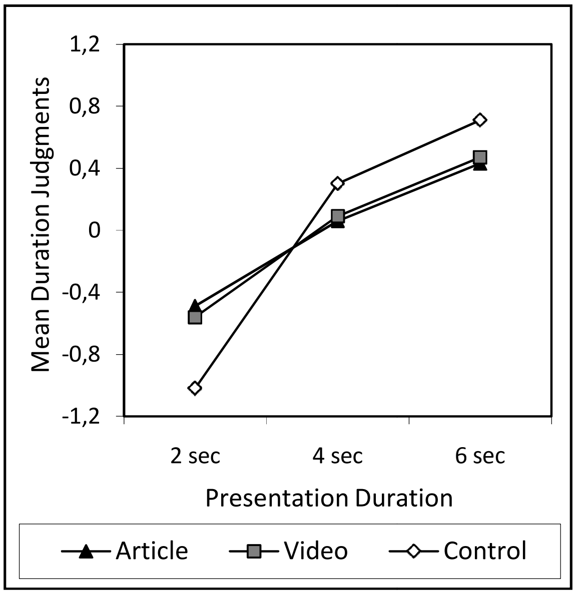
	Article			Video			Control			Comparison		
	t	*p*	*g*	*t*	*p*	*g*	*t*	*p*	*g*	*t*	*p*	*r*
Sensitivity to Frequency	8.22	.000	1.75	12.5	.001	2.67	58.1	.000	12.4	4.17	.000	.46
Sensitivity to Duration	3.93	.001	0.84	4.00	.001	0.85	11.5	.000	2.45	2.63	.006	.31
Influence of Frequency on Duration	2.11	.024	0.45	2.73	.007	0.58	6.22	.000	1.33	1.58	.060	.20
Influence of Duration on Frequency	4.12	.000	0.88	6.81	.000	1.45	9.17	.000	1.96	3.07	.002	.36

Note: For all repeated-measures contrast analyses, *df*=21, and for the between-groups analyses, *df*=63, *p* values are one sided.

Sensitivity to stimulus durations. Figure 6 shows the mean *z*-standardized duration estimates for each level of the actual stimulus durations, averaged across the three frequency levels. Apparently, sensitivity to stimulus durations differs between the three experimental conditions. The contrast analyses for sensitivity to durations reveal large effect sizes in each of the three conditions with an especially high effect size for the control condition (see Table 2). The comparison of the experimental conditions by means of a between-groups contrast analysis supports the hypothesis (the more attention is distracted from the stimuli, the lower the sensitivity to durations) by a moderate effect size (Table 2, Comparison).

Figure 6

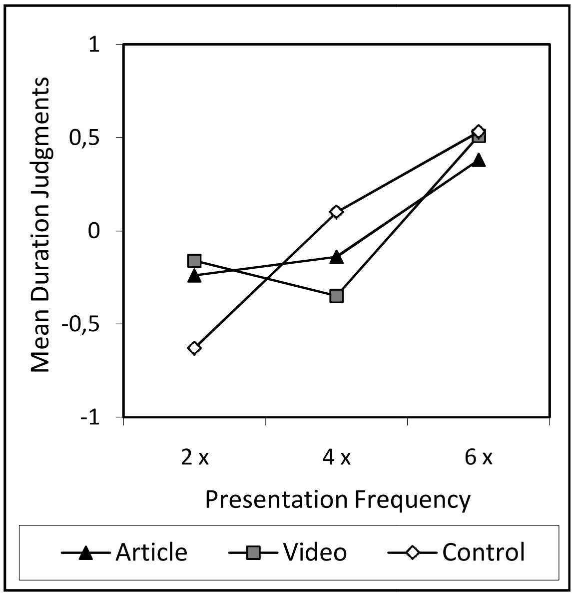
Sensitivity to Stimulus Duration (*z*-transformed means), Experiment 2.



Influence of stimulus frequencies on duration judgments. Mean *z*-standardized duration estimates for each level of the stimulus frequencies, averaged across the three duration levels are displayed in Figure 7. The influence of stimulus frequencies on duration judgments differs between the three experimental conditions. This notion is confirmed by moderate effect sizes in the article and the video conditions, and a large effect size in the control condition (see Table 2). The comparison of the experimental conditions by means of a between-groups contrast analysis does not support the hypothesis (the more attention is distracted from the stimuli, the lower the influence of stimulus frequencies on duration judgments), although a low effect size confirms a tendency of the results toward this assumption (Table 2, Comparison).

Figure 7

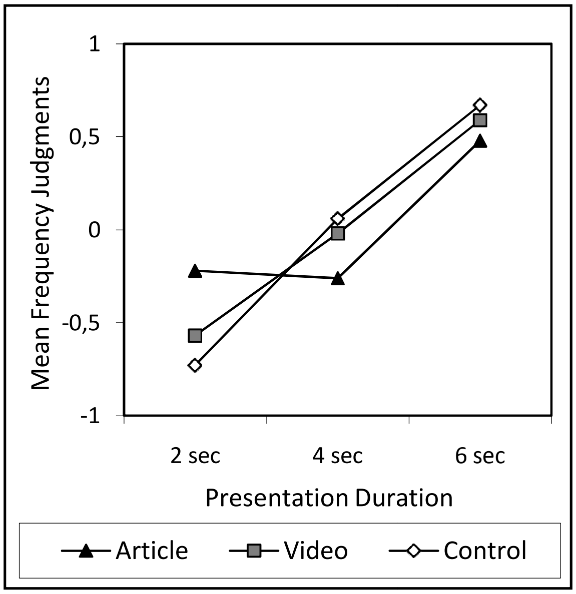
Influence of Stimulus Frequency on Duration Judgments (*z*-transformed means), Experiment 2.



Influence of stimulus durations on frequency judgments. Mean *z*-standardized frequency estimates for each level of the stimulus durations, averaged across the three frequency levels, are shown in Figure 8. Frequency judgments systematically covary with stimulus durations in each of the experimental conditions, although we obtained differences in the strength of this covariation between the experimental conditions. The contrast analyses for the influence of stimulus duration on frequency judgments reveal large effect sizes in each of the three conditions (see Table 2). The comparison of the experimental conditions by means of a between-groups contrast analysis supports our hypothesis (the more attention is distracted from the stimuli, the lower the influence of stimulus durations on frequency judgments) by a moderate effect size (Table 2, Comparison).

Figure 8

Influence of Stimulus Duration on Frequency Judgments (*z*-transformed means), Experiment 2.

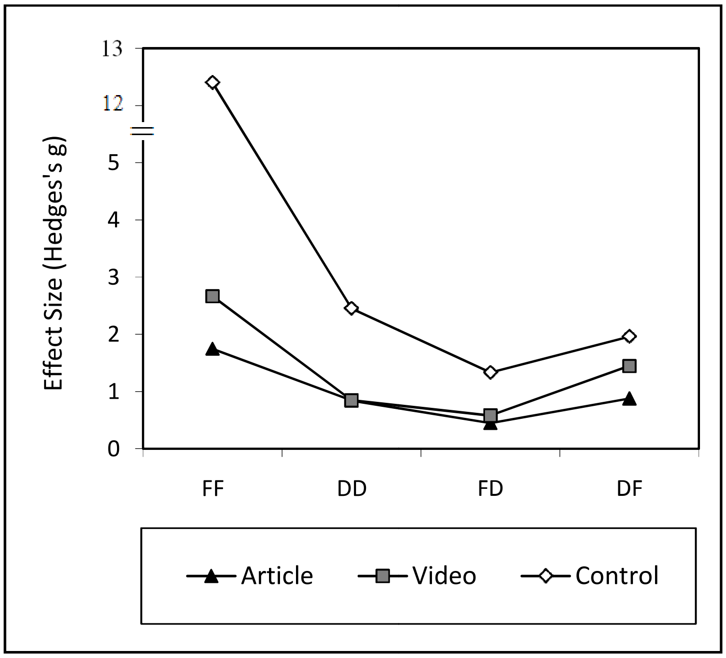


Discussion

Because of the complex results, Figure 5 gives an overview of the different effect sizes concerning (1) the sensitivity to frequencies, (2) the sensitivity to stimulus durations, (3) the frequency effect on duration judgments, and (4) the duration effect on frequency judgments, separately for each of the experimental conditions. As hypothesized, we find high sensitivities to stimulus frequencies in each experimental condition with an especially large effect size when no secondary task was presented (control condition). As assumed, sensitivity to frequencies is lower when more attention is distracted by the secondary task. In a similar vein, sensitivity to durations is high in each experimental condition. As for sensitivity to frequencies, sensitivity to durations is highest in the control condition. When attention is distracted by a secondary task, sensitivity to durations decreases, although no difference was found between the two dual-task conditions. Furthermore, we find a high influence of stimulus frequencies on duration judgments in the control condition. In the two dual-task conditions, however, this effect is moderate. Nevertheless, the frequency effect on duration judgments decreases slightly with decreasing available attentional resources. Finally, a high influence of stimulus durations on frequency judgments is obtained in each of the experimental conditions. This effect decreases slightly when more attention is distracted from the stimuli.

Figure 9

Effect sizes (Hedges' *g*) for FF, DD, FD, and DF of the three experimental conditions.



Note: FF = Sensitivity for Stimulus Frequency, DD = Sensitivity for Stimulus Duration, FD = Influence of Stimulus Frequency on Duration Judgments, DF = Influence of Stimulus Duration on Frequency Judgments

General Discussion

In the present paper we aimed to examine the judgments of frequency and duration in order to draw conclusions about the underlying processing mechanisms. The starting point of our analysis was the assumption that the often obtained asymmetrical relationship between frequency and duration judgments is due to specific methodological characteristics of the previous studies in this domain. In particular, these studies were set up in a way that did not allow participants to allocate sufficient attentional resources toward the stimuli to adequately encode their presentation durations. Whereas frequency processing requires only little attention, the encoding of duration requires focusing attention on a stimulus for the complete presentation duration.

In previous studies analyzing judgments of frequencies and durations simultaneously, usually a large number of stimuli was presented and, moreover, the stimuli used were usually of low personal relevance. Both factors might have reduced the attention directed toward the stimuli. Accordingly, these studies demonstrated a high sensitivity to frequencies and a low sensitivity to durations.

The present results suggest that attention is an important factor that moderates the encoding of duration and therefore has implications about judgments of both frequencies and durations. If there is a common mechanism underlying the processing of frequency and duration, a mutual influence should only be found, if stimulus frequencies and durations are encoded sufficiently. If stimulus duration is not encoded completely but rather for the first one or two seconds after stimulus onset, then the perceived stimulus duration will hardly vary with respect to actual stimulus durations, and thus, will influence frequency judgments scarcely. Hence, no (or just a weak) influence of stimulus duration on frequency judgments will be found – even if there is one common mechanism underlying frequency and duration processing. In this case, it becomes impossible to decide whether the asymmetrical result pattern occurs due to the not completely processed stimulus durations, or due to stimulus frequency and duration being stored separately.

Within the studies presented here, we examined the effect of attention on the interactions of frequency and duration judgments. In Study 1, we directed attention toward the stimuli during the complete stimulus duration (by means of the presentation of traffic simulations). As a consequence, we obtained a higher sensitivity to durations and a mutually influence between frequency and duration judgments. In Study 2, we distracted attention from the stimuli by means of a secondary task. Results showed a lower sensitivity to both, stimulus frequencies and durations as well as a lower mutual influence between the judgments.

Taken together, these results support the hypothesis that one common mechanism is underlying the processing of frequencies and durations. Presumably, information about stimulus frequencies and durations are not stored separately, but rather within the same memory structures, thus facilitating the alignment of the frequency and duration perceptions, before judgments are generated. In most cases, this procedure might be very useful, due to the fact that frequency and duration are two event characteristics that are frequently linked. Most of the time, a stimulus appearing more frequently, will also be present for an overall longer period of time and vice versa. The existence of one common mechanism for the processing of frequencies and durations, presumably, would be an economical and effective – although not entirely faultless – strategy of our cognitive system. If there is such a common mechanism, as suggested by our results, this could have consequences on a variety of judgments in applied settings. To more fully understand the processes involved and to make precise predictions about the respective judgments, the next step is now to develop a comprehensive model of frequency and duration processing that allows for the integration of the existing (and on the first sight conflicting) findings. Because frequency and duration are such basic ingredients in many of our daily judgments, it might turn out that such model will be an indispensable part in comprehensive cognitive architectures.

5 Summary and Conclusions

The findings of all the studies reported here support the assumption that our perceptions of frequencies and durations influence each other mutually under certain conditions. Frequency judgments, influenced by stimulus durations, as well as duration judgments, affected by stimulus frequencies, mirror this interaction of frequency and duration processing. However, this interaction is obtained only if sufficient attentional resources are available for the encoding of stimulus frequencies and durations. That is a crucial point, especially for duration processing, due to the fact that more attention is necessary which has to sustain for the complete stimulus durations to facilitate the entire duration processing. Various factors might impede (or facilitate) successful duration processing. In Manuscript 1, we learned that a high cognitive load, induced for example by a high number of presented stimuli or a complex task, impedes the processing of stimulus durations, but not the processing of frequencies. As a consequence, a low sensitivity to durations and an asymmetrical relationship between frequency and duration judgments occur. Judgments of stimulus duration are strongly influenced by stimulus frequencies, while judgments of frequency, in contrast, are almost independent from presentation durations. In addition, when cognitive load is low, a high sensitivity to both, stimulus frequencies and durations as well as a mutual interaction between frequency and duration judgments is obtained.

Moreover, in Manuscript 2 and 3, it was demonstrated that sensitivity to frequencies and durations are increased when more attention is directed toward the stimuli; and it is decreased when attention is distracted from the stimuli. The presentation of emotionally relevant stimuli, or a task that directs attention for the complete stimulus duration toward the stimuli (as seen in Manuscript 2) as well as the presentation of realistic stimuli (as seen in Manuscript 3) increases attentional resources, and thus facilitates the mutual interaction between frequency and duration judgments.

Taken together, these results support the hypothesis that one common mechanism is underlying the processing of frequencies and durations, as suggested by Walsh (2003) in his theory of magnitude, which assumes that time, space and quantity are part of a common magnitude-representation system, as well as by neuropsychological research (Buhusi & Meck, 2005; Cordes et al., 2007). Presumably, information about stimulus frequencies and durations are not stored separately, but rather are matched before they are stored in the same memory structures and judgments are generated. In most cases, this procedure might be very useful, due to the fact that frequency and duration are two characteristics of stimuli or events that are frequently linked. Most of the time, a stimulus that appears more frequently, will also be present for an overall longer period of time. For example, when waiting in front of a large number of red lights on the way to work, it will appear to us as if we were waiting for an overall longer period of time — an impression that indeed will be correct in most cases, though not necessarily in each case. The existence of one common mechanism for the processing of frequencies and durations, presumably, would be an economical and effective, although not always faultless, strategy of our cognitive system.

A model that considers such a common processing mechanism and that is able to explain and predict judgments of frequency and duration is the PASS-T model (Sedlmeier & Winkler, 2009) — an extension of the PASS (Probability ASSociator) model (Sedlmeier, 1999, 2002). PASS-T is an associative learning model that defines events or objects by its features. Each time a stimulus occurs and receives attention, the representation resulting for this stimulus is strengthened. Due to the existence of a pacemaker (similar to the pacemaker within the attentional-gate model, Zakay & Block, 1997), not only stimulus frequency, but also stimulus duration is represented within the model: The representation of a stimulus is strengthened by each presentation of this stimulus as well as by each time step of the pacemaker, as long as attention is focused on this stimulus. In addition, the model, by virtue of its associative learning mechanism, acquires and stores information about the time lag between each stimulus presentations. The associative memory built up by PASS-T in the course of repeated stimulus presentation is the basis for both, symmetric or asymmetric judgments. Judgments are performed by comparing the activation in PASS-T's memory to either of two reference memories: one for frequencies and another for durations, depending on the judgmental task.

Further research is needed to examine the assumptions and predictions of this or similar models, and to compare them with findings from behavioral studies on frequency and duration processing. Furthermore, the comparison of the findings from human frequency and duration processing with the results of animal research might give useful information for a better understanding of the basic cognitive processes involved in judgments of frequency and duration.

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Appendix

Stimuli used in the Experiments of the Manuscripts 1 and 2

Male First Names	Female First Names
Andreas	Anna
Christoph	Claudia
Daniel	Ella
Fabian	Karin
Felix	Katja
Florian	Klara
Julian	Laura
Lukas	Lea
Marcel	Lena
Martin	Lisa
Michael	Lydia
Moritz	Maria
Peter	Nadine
Philipp	Nina
Robert	Sandra
Stefan	Sarah
Thomas	Sonja
Tobias	Sophie

Eidesstattliche Erklärung

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbstständig verfasst und keine anderen als die angegebenen Hilfsmittel verwendet habe.

Chemnitz, 21. April 2009

Isabell Winkler