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# Uni-, bi- and tri-modal warning signals: Effects of temporal parameters and sensory modality on perceived urgency

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ABSTRACT

Multi-sensory warnings can potentially enhance risk communication. Hereto we investigated how temporal signal parameters affect perceived urgency within and across modalities. In an experiment, 78 observers rated the perceived urgency of uni-, bi-, and/or tri-modal stimuli as function of 25 combinations of pulse duration (range 100–1600 ms) and inter pulse interval length (100–1600 ms). The results showed that perceived urgency increases with signal rate. Inter pulse interval showed a larger effect than pulse duration and the largest differences in perceived urgency as function of inter pulse interval occurred at the smallest pulse duration (100 ms). The effects of pulse duration and inter pulse interval were universal across modalities. Bi- and tri-modal signals were perceived as more urgent than each of their uni-modal constituents. We conclude that temporal parameters can be deployed to construct integrated, multi-sensory warning signals with a pre-specified degree of perceived urgency.



## 1. Introduction

In modern operating environments people are frequently confronted with warning signals presented in different sensory modalities. Warning signal optimisation requires a match between warning criticality and perceived warning urgency (operationally defined as the impression of urgency that a signal evokes in an observer). Although it is known that perceived signal urgency depends on effective multi-sensory integration, it is currently not known how the spatio-temporal characteristics of the individual signal channels contribute to the overall perceived signal urgency. Here we investigated the effects of pulse duration and inter pulse interval on the perceived urgency of uni-, bi- and tri-modal (auditory, visual and tactile) signals.

### *1.1. Toward multi-modal warning signals*

Operators working in information rich environments such as in medicine, aviation and road transport may suffer from an overabundance of warning signals presented in different sensory modalities. For instance, a midsize car may already have several flashes, beeps and even buzzes in the driver's seat linked to cruise control, collision avoidance, parking assistance, communication, and entertainment systems. Lack of integration of these signals may result in increased workload, distraction, and ultimately compromise safety (Carsten and Nilsson, 2001; ECMT, 1995; Rumar, 1990).

New display technologies in amongst others cars and aircraft provide excellent opportunities to integrate auditory, visual and more recently also tactile warning signals (e.g. vibrations presented through a car seat, De Vries et al., 2009; Hogema et al., 2009). Potential advantages of multi-sensory warning signals are faster reactions (Bernstein et al., 1969; Diederich and Colonius, 2004; Hershenson, 1962) and reduced risk of sensory overload (Hancock et al., 2013; Lu et al., 2013; Ngo et al., 2012; Prewett et al., 2012; Spence, 2011). However, effective multi-sensory integration requires spatio-temporal and semantic congruency across sensory modalities (Kolers and Brewster, 1985). At a perceptual level, multi-sensory integration is optimal when stimulation in different sensory modalities occurs approximately at the same time and originates from the same location. In addition to perceptual congruency, signals should also be congruent semantically, including perceived urgency of warning signals. Currently, multi-sensory warning signals are being applied at an increasing scale, and improved knowledge on optimal integration is indispensable to make full use of their potential advantages.

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Research into the design of uni-sensory warning signals shows that many stimulus parameters may affect perceived urgency, including frequency, intensity, speed, colour, waveform, and inharmonicity (Hellier et al., 1993; Chan and Ng, 2009). Several of these parameters are modality specific (e.g. visual colour or auditory inharmonicity), and therefore less suited for optimal integration across senses, while others like speed and intensity are a-modal parameters. For warning signals, temporal parameters are very relevant since they may have a large effect on perceived urgency (e.g. Patterson, 1982), they are not modality specific, and they are critical in multi-sensory integration. In addition, even simple display technologies are able to present on–off rhythms of a light, a tone or a vibration, making temporal patterns an attractive choice from both a fundamental and applied perspective.

### 1.2. Temporal parameters in warning signals

Simple warning signals can be defined by two temporal parameters which we will denote as pulse duration ('on' time) and inter pulse interval ('off' time). Warning patterns are often referred to with their rate or speed expressed as the number of cycles (i.e., one pulse and one inter pulse interval) per unit of time; usually per second (expressed in Hz) or minute (expressed as e.g. flashes per minute or fpm). Because using signal rate has the disadvantage that pulse and interval length remain unspecified, we report pulse duration and interval length separately when possible.

### 1.3. Effects of temporal warning parameters in uni-modal signals

#### 1.3.1. Auditory signals

For non-speech audio, Blattner and her colleagues (Blattner et al., 1989; Sumikawa et al., 1986) proposed an approach to construct (warning) signals based on the musical qualities of auditory information using relatively simple tones. These simple tones can be combined to form more complex "earcons". Patterson (1982) and Edworthy et al. (1991) already stated that temporal aspects are critical in distinguishing between sounds and that speed has probably the strongest influence on perceived urgency. Later work by amongst others Brewster (1994) showed that rhythm and tempo variations (i.e. speeding up or slowing down the patterns) are an effective method for differentiating earcons. The range of signal rates generally applied is based on the standard work by Hellier et al. (1993) who used a 200 ms tone and inter pulse intervals ranging from 9 to 475 ms (i.e. rates of 1.5–4.8 Hz). Through applying Stevens' power law to the perceived urgency data, they concluded that a speed increment of factor 1.6 (i.e., 60% increase) is required to double the perceived urgency. This increment compares favourably to the factors needed in repetition (4), fundamental frequency (6), and inharmonicity (307). Similar stimuli are still used today for warning signals (e.g., Gonzalez et al., 2012), and although the auditory sense is able to process much higher signal rates, these are seldomly applied. Guillaume et al. (2003) found increasing urgency ratings for signal rates in between 1.8 and 6.7 Hz, and Zobel (1998), studying the usability of a parking assist system, found that signal rates below 6 Hz are perceived as less urgent than rates above 6 Hz. Small pulse durations (<80 ms for complex and <30 ms for simple earcons) decrease perception and can better be avoided (Brewster et al., 1995).

#### 1.3.2. Visual signals

Guidelines for optimal rates of visual warning signals are well established and part of international recommendations and standards in for instance aviation and road transportation (UNECE, 2002). Although the upper limit of the signal rate is theoretically determined by the flicker-fusion frequency (about 30 Hz), a rate of 10 Hz (i.e. a pulse duration of 50 ms and an inter pulse interval length of 50 ms for a symmetrical pattern) is considered to be the maximum useful rate (e.g., Turner et al., in press). However, rates of 1–4 signals per second (Markowitz, 1971; McCormick, 1976) are recommended. Within this range, higher rates resulting in faster behavioural responses and higher perceived urgency (e.g., Turner et al., in press; Chan and Ng, 2009). Visual warning signals are often designed as flashes: signals with a pulse duration that is shorter than the inter pulse interval. Short flashes in which the pulse duration is less than 1/3 of the inter pulse interval length are visually most effective (Bartley and Nelson, 1961). However, as with auditory signals, research has focused on signal rate rather than on pulse duration and inter pulse interval as independent parameters.

#### 1.3.3. Tactile signals

The body of research on using tactile displays for warning signals is still small, but the increasing inclusion in multi-modal interfaces resulted in a steady growth over the last decade. According to amongst others ETSI (2002) and ISO (2009) guidelines, using temporal parameters is one of the preferred choices to code information on a tactile display. With respect to design guidelines for tactile temporal patterns, Van Erp (2002) recommends that both the pulse duration and the inter pulse interval should be at least 10 ms (see also Gescheider, 1974; Petrosino and Fucci, 1989), i.e. a pulse rate of 50 Hz. However, such a high pulse rate is not feasible with common tactile actuator technology based on vibration motors which allows maximum rates of 5–10 Hz (Van Erp, 2007). Van Erp and Spapé (2003) showed that, as with auditory earcons, speed or tempo is one of the fundamental dimensions of so-called tactons. Several applications have used (faster) rhythms to code for (increased) urgency or (decreased) distance in aviation and driving. For instance, Van Erp and Van Veen (2004) used decreasing inter pulse intervals in an in-vehicle tactile navigation system to indicate an approaching intersection. Carlander and Eriksson (2006) used a similar paradigm to code threat urgency in a combat vehicle. Only very recently, researchers started to look more thoroughly at the use of tactile displays for warning signals (Haas and Van Erp, 2013) and at the relation between tactile patterns and perceived urgency. Using the same parameter setting as Hellier used for auditory warnings (Hellier et al., 1993), Pratt et al. (2012) showed that for 200 ms tactile pulses, perceived urgency of a 2.5 s pulse train increases with a decreasing inter pulse interval ranging from as low as 9 ms to 475 ms (i.e. higher pulse rates are perceived as more urgent).

#### 1.3.4. Multi-sensory signals

The increasing use of multi-modal interaction also resulted in studies on multi-sensory warning signals. A common application is the combination of a visual and an auditory verbal or non-verbal signal. Meta-analyses show that multi-sensory signals generally result in more adequate behavioural responses and increased perceived urgency, but not in all situations. For instance, effects may differ as function of task, environment or operator workload (Lu et al., 2013) and whether the signals across modalities are complementary or redundant (see Spence and Ho, 2008 for an overview). Often, the signals in different modalities are complementary and not mere copies, e.g. a flashing light and a spoken message (Chan and Ng, 2009). Although purely redundant multi-sensory signals are applied (e.g. the dashboard light and beep of the turn indicator in a vehicle), the effect of for instance temporal parameters and possible multi-sensory additive effects have not been systematically investigated. Researchers mainly focused on scaling the urgency across auditory and visual modalities (Edworthy and Hellier, 2006; Hellier and Edworthy, 1999; Wogalter et al., 2002; but see Baldwin et al., 2012 for possibly the first work including the tactile modality).