An agent based modeling approach to explain the perception of environmental stressors

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Abstract - *Artificial intelligence traditionally draws inspiration from biological systems, in order to achieve a similar degree of intelligence in artificial systems. More recently, ideas from computational intelligence are being applied successfully in achieving a better understanding of the mechanisms underlying the emergence of group-level patterns in biological and sociological systems. In this paper, the use of an intelligent software agent for mimicking the human response to environmental stressors is proposed. The conceptual model for a single individual contains strongly interacting submodels for sensory observation of the environment, cognition and emotion. A partial implementation of this model, focused on auditory perception, is applied to gain additional insight in the underlying mechanisms that lead to the emergence of noise annoyance at the community level. In particular, it is shown that this new approach may give a possible explanation for the difference in annoyance between road and railway traffic for equal sound level, as is observed in numerous noise surveys and laboratory experiments.*

Keywords: intelligent agent, sensory perception, environmental stressor, noise annoyance.

1 Introduction

Health, well-being, perceived safety etc. are increasingly higher ranked aspects of good quality of life, in those areas of the world where economic well-being has reached an acceptable level. In order to efficiently fulfil these demands, it is useful to study in more detail how the perception of the quality of the living environment emerges – a process that is classically called subjective. Assessing the effects (annoyance, activity disturbance,…) on man of *environmental stressors*, such as noise or odour, is a complex problem in which physics, psychophysics and psychology all play an important role.

By far the largest body of knowledge relating environmental exposure to noise, odour, air quality, safety etc. and the effects and reactions caused by it, is based on epidemiologic research. Large groups of people are questioned about their living environment, and effects are mainly expressed on a population averaged basis. Regarding noise in particular, researchers have been focusing very strongly during the past decades on deriving quantitative relationships between average noise levels and community noise annoyance [1]. Although rather successful in describing the reaction of large populations, this approach, in which experimental observations or surveys of large groups of individuals are data-mined, does not explain *how* psychophysical, cognitive and behavioral responses to environmental stressors emerge.

In this context, it is worth mentioning that the increasing availability of computing power has made it possible to extract knowledge on the internal mechanisms governing the behaviour of single individuals, by observing group behaviour resulting from a large number of simulated individuals, sometimes referred to as synthetic populations. For example, this paradigm has been applied to study various structural and behavioral patterns in biological systems, such as termite mounds or the coordinated movements of a school of fish. Patterns were shown to emerge from the interactions between numerous individuals or within a single individual, acting according to a minimal set of rules of thumb (see e.g. [2] for a review).

In this work we propose to use these computational techniques to unravel the underlying mechanisms of human perception of and reaction to environmental stressors. In the next section, a human mimicking model for the perception of environmental stressors by an individual will be outlined from a conceptual point of view. The most important factors influencing the perception of environmental stressors will be distinguished. Ideally, the sketched approach yields a unified model allowing to relate the observed modifying factors in environmental impact assessment to the underlying basic physical, psychophysical and psychological principles, and thus, to reproduce and explain, in a qualitative way, trends and dependencies which are observed in epidemiological research. Section 3 will describe a partial implementation of this model, focused on auditory perception and embodying current knowledge on psychoacoustics, and will give some simulation results.

2 Methodology

2.1 Conceptual model layout

A model describing a single individual will have to include the sensory observation of the environment, together with the internal mechanisms of perception in the

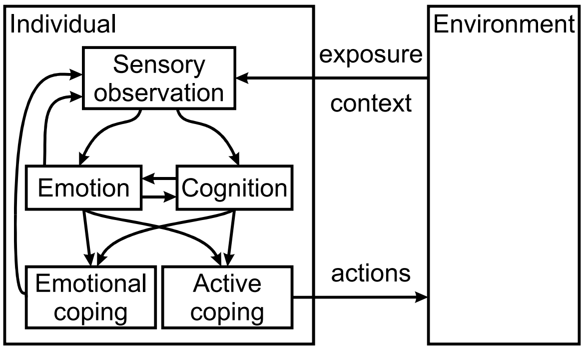

Figure 1 – Layout of the general model.

broadest meaning of it. Sensory observation of environmental stressors may trigger cognitive, emotional or behavioral reactions. A suitable model should therefore at least consist of three strongly interacting submodels: a model for sensory observation, a model for cognition (including memory) and a model for emotion. Figure 1 summarizes the most important principles of the proposed model.

A bottom-up approach requires a *causal* model for perception and evaluation of the living environment. Inclusion of causality naturally leads to the inclusion of temporal aspects: the flow of actions and/or emotions that follow upon each other have an ordering in time. Explicitly accounting for this by using a time-domain approach also provides the opportunity to model the interaction of factors influencing perception and evaluation. Consider for example active coping: to be effective, the ability to cope has to overlap with the period of increased exposure.

Next to the level of exposure, sensory observation of a stressor will be influenced by the environmental context of the individual (at home, at work etc.) and its activity, and by several personal (time-varying) factors, such as the level of attention for and the possible habituation to the stressor. In this work, alertness is used to model the process of focusing attention to the particular stressor. Alertness itself will be influenced by time (circadian variation, see e.g. [3]) and the current activity. For example, sleeping lowers the alertness to external stimuli, while high levels of alertness towards environmental stressors can be expected during relaxing. The concept of alertness reflects that within our mind, only a limited amount of resources are available. When multiple inputs are presented, attention has to be divided amongst them. This division is dependent on the task and goals at hand. During a task that requires significant mental resources, alertness to environmental stressors is likely to be lower (see e.g. [4]). The proposed model includes several feedback paths. Habituation in our context specifically denotes the short term habituation occurring at sensory level. Emotion may play a role in this (see [5]). The perception model includes long-term effects (often called adaptation) via an emotional coping path that could lead to some form of denial. Active or behavioral coping mechanisms are assumed to mainly have an effect on exposure itself.

Sensory events, which form the output of the submodel for sensory observation, may trigger a sequence of changes in the cognitive and emotional subsystems. These reactions are influenced by the active state of both subsystems. The emotional state or *gestalt* of an individual is defined as the state of the system of variables describing the individual emotions. According to [6], emotional change may be regarded as a transition in a complex dynamic system. A large number of computational models for emotion have been proposed in the past (see e.g. [6][7][8]). In this work, focused on environmental stressors, the emotional variables of interest are anger, anxiety and annoyance. An additional variable, background stress, may also be introduced to group all non-specific emotional variables that may influence the emotional reaction to a stressor, such as the stress related to an activity. The sensitivity to the environmental stressor is the most important personality trait, modifying the emotional reaction.

Cognitive processes also influence the perception of stressors. Knowledge about the source, possibly influenced by media etc., contribute to perception. This knowledge can determine the attitude towards the source, or may create fear for the source. However, not all effects need to be negative. For example, a reduction in annoyance is possible when the activity causing the stressor to originate is perceived as socially or economically advantageous. Certain contexts or environments also include a pattern of expectations. For example, when walking through a forest, environmental noise or odour is evaluated differently, as compared to when walking in a city. There is strong evidence for an influence of emotional states on cognition, and of cognition on emotion (see e.g. [9] or [10] for a review). Generally, it is found that cognitive reactions that are capable of eliciting the current emotion are most likely to occur [7].

Two recent computational models are of particular interest for implementing the cognition and emotion submodels: *modeling field theory* [11] and *confabulation theory* [12]. Both approaches describe an iterative transition from fuzzy sets of options to crisp thoughts. This transition may be triggered by sensory input. It is proposed to model the drive for learning through the emergence of an aesthetic emotion [11]. Making this emotion arise when the sensory input matches the internal model of the living environment is particularly suitable for our goal.

Observed stressors may or may not be appraised as taxing or exceeding personal resources. Following the ideas of Lazarus on stress, appraisal and coping [13], it is assumed that a negative appraisal can lead to various styles of *coping*. Both cognitive and behavioral reactions to the stressor are considered, each leading to different ways of coping. An example of active coping is closing the windows. Important aspects in the process of coping are the individual coping style, the ability to cope (depending on the available internal coping resources, the current activity and other contextual factors), the effectiveness of the coping actions and the time scale. Note that the process sketched in Figure 1 is a dynamic one. After a first appraisal and emotional and cognitive reactions, reappraisal may and will occur within the newly developed context, possibly triggering new coping reactions.

2.2 Validation and knowledge extraction

The proposed model treats each individual as unique and tries to model, as much as possible, the personal factors that modify the effect of environmental stressors on an individual basis. Of course, this is only possible to a certain extent. Although an important body of knowledge has been extracted from well controlled laboratory experiments on perception, not all parameters of the models to be used are readily available from literature, and certainly not when individual variations between people are considered; some are even hard or impossible to measure. For some of the parameters, the variation over a population can be expressed using probability distributions. By simulating a large number of individuals and drawing samples from the appropriate distributions, the simulated population will exhibit the same statistics on the observed variables as found in observations. For parameters that exhibit hard imprecision, because e.g. the underlying variable is vague, a fuzzy set representation can be used [14][15][16].

By implementing a model as a software agent, one is forced to concretize vague ideas, to quantify model parameters, or even to formulate hypotheses and to add additional submodels, of which the quality is measured by the agreement of the model predictions with empirical investigations. To query the state of mind of a simulated population of individuals, virtual questionnaires can be used. They measure the (fuzzy) similarity between the cognitive association evoked by the question and the available answers proposed in the questionnaire. Because of the stochastic nature of this type of modeling, it is as useful to compare the predicted spread in responses, caused by inter-individual variability, between model and experiment, as it is to compare mean values. This is particularly true when plotting experiment and simulation as a function of an environmental indicator.

A good model will be developed gradually, by iteration between software implementation and psycho-physical and psychological knowledge. Building the model itself will therefore make the knowledge on the various mechanisms that play a role in the emergence of effects caused by environmental stressors explicit.

3 Modeling noise annoyance

3.1 Mathematical description

To concretize the idea, the focus is put on a specific environmental stressor, noise, and on a specific effect, annoyance. In view of feasibility of the numerical effort, details of the auditory processing of the physical input are not considered: time-varying descriptors of what is observed by the auditory system form the input of the model, rather than the audio signal. In particular, a combination of sound level, psychoacoustic descriptors (loudness, pitch, sharpness, roughness etc.) and descriptive measures (e.g. the sound of a car or a train, auditory distance to the source) is considered. For simplicity, we will discuss only the sound level in this paper. The model input is expressed as a time series of $L_{\mathrm{Aeq,1s}}$ values, denoting the energy equivalent A-weighted sound pressure level, averaged on a 1-second basis.

The key hypothesis states that *noise has to be noticed, before it can become annoying*. This has already been stressed in earlier work [17][18]. Noise exposure contains a mixture of sounds. Part of this mixture is regarded as background, since those sounds are of no or little interest for the effect under study (e.g. the sound of wind, rain, birds). These sounds are not continuously noticed. A *notice-event* is defined as an instant of attention focus to the noise. The occurrence of a notice-event depends on the level of the sound above the background, the degree of alertness of the listener, the current activity (which may produce masking noise) and the amount of habituation that may have occurred. Note that a notice-event can occur whenever one of the above parameters changes. E.g. a sudden increase in alertness may trigger a notice-event, although the sound level did not change.

The notice-event has a well defined starting point in time. The condition used to identify the start of a notice-event is primarily based on the difference between, at the one hand, the sound level L_s produced by the modeled individual itself and the natural background hum L_n, and at the other hand, the level L_i of the intruding sound entering its living environment,

$$L_i - L_s - L_n > T(t) \tag{1}$$

in which we explicitly introduced the dependence of the *notice-threshold* T on the time t. The end of a notice-event is defined in a similar way. It should be noted that noticing is source-specific.

The notice threshold will depend on the alertness of the individual, which gathers various aspects. As already mentioned, alertness will depend on the time of the day, and on the current activity. Results from a recent field experiment [19] also suggest a dependence on noise sensitivity; an effect which is found in a less pronounced form in [20]. Very little is known on the dependence of the notice-threshold on alertness. It is safe to assume that T decreases monotonously with alertness $a(t)$, hence for simplicity, we approximate it by a linear function on a decibel scale

$$T(t) = T_{base} - f \cdot a(t) \tag{2}$$

where f is used as a general constant determining the influence of the alertness on the threshold.

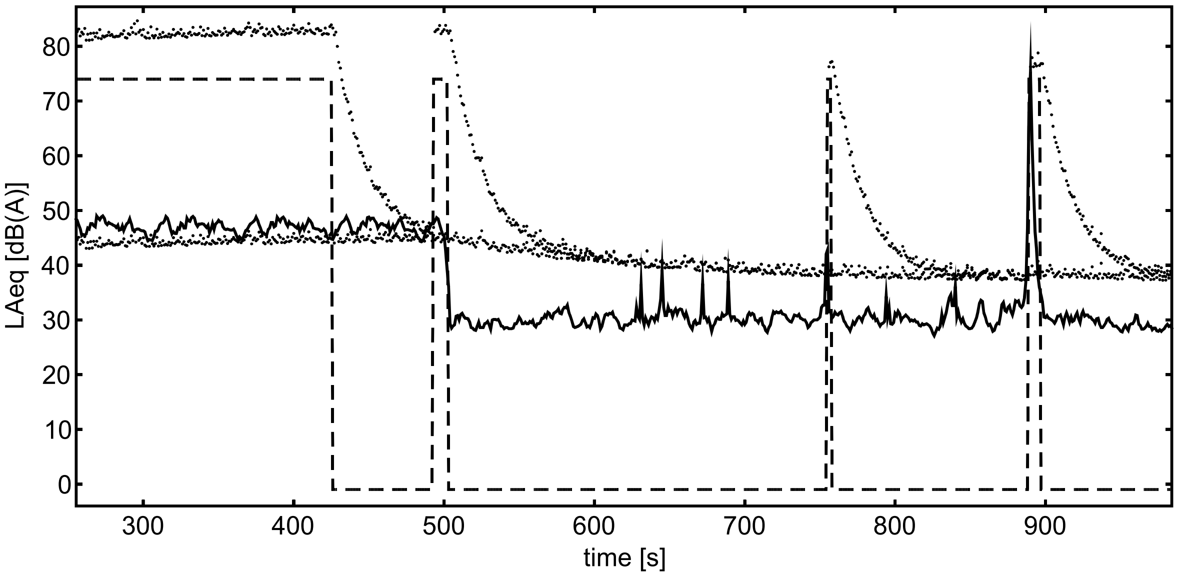

Figure 2 – Excerpt of an $L_{\text{Aeq,1s}}$ time series simulation (solid lines), together with the thresholds for the start and end of a notice-event (upper and lower dots), and the detected events (dashed lines).

After a sound is noticed, subsequent peaks in the intruding sound will not trigger the beginning of a new notice-event, unless they are sufficiently more noticeable. The psychophysical mechanism closest to explaining this is *gating* (perceptual and attentional). The gating condition holds slightly longer than the event that was first noticed continues, since it is known that non-negligible time constants are involved in the process [21]. Hence, *T(t)* is extended to model gating:

$$T'(t) = \begin{cases} T(t) + T_{new} & t_{begin} < t < t_{end} \\ T(t) + T_{new} \cdot \exp\left(\dfrac{t_{end} - t}{\tau_g}\right) & t_{end} \le t \end{cases} \tag{3}$$

where t is the current simulation time and t_{begin} (t_{end}) mark the begin (end) time of the last notice-event. T_{new} determines the extra sound level events need to have, compared to the current sound event, to defeat the gating mechanism. Reported constants τ_g range up to 1s for attentional gating.

Because of habituation, the effective duration of noticing a sound can be shorter than what is expected from the raw sound levels. Habituation may also suppress the emergence of new notice-events, because the individual has become used to a certain sound exposure. Although it seems natural that habituation is limited [22], it is assumed that usual sound levels of environmental noise do not cause sensory saturation. Habituation *h(t)* is assumed to be proportional to the exponentially averaged sound level over a long time:

$$h(t) = \frac{1}{\tau_h} \int_{-\infty}^{t} L_i(u) \cdot \exp\left(\frac{u - t}{\tau_h}\right) du \tag{4}$$

Time constants τ_h involved in stimulus specific habituation in audition vary between several seconds to several minutes [21]. Furthermore, it is assumed that the effect of short-term habituation is mediated through a reduced alertness towards the intruding sound,

$$a(t) = a_{activity}(t) - C_h \cdot h(t) \tag{5}$$

where the constant C_h is determined from the observation that $f \cdot C_h$ is the maximum magnitude of the notice-threshold shift that can be caused by habituation.

When a sound is noticed, attention is drawn to it. Because of this elevated state of alertness, events in the immediate future are more likely to be noticed. This effect counteracts habituation, but is expected to be relevant on a smaller time scale (a couple of seconds). Since attention focusing is instantaneous and diminishes over time, it may be modeled by a step in the alertness that exponentially fades away,

$$a'(t) = a(t) + C_a \cdot \exp\left(\frac{t - t_{begin}}{\tau_a}\right) \tag{6}$$

where t_{begin} denotes the begin time of the last notice-event and τ_a denotes the time constant involved in attention focusing. Again, C_a is determined from the observation that $f \cdot C_a$ is the equivalent reduction in noticing threshold caused by the attention focusing of the modeled individual.

A notice-event is appraised by the modeled individual based on a number of characteristics of the intruding sound, of which the most important one is its loudness. It is approximated by the integrated A-weighted acoustic energy between the begin t_{begin} and the end t_{end} of the notice-event:

$$E = \int_{t_{begin}}^{t_{end}} 10^{L_i(t)/10} dt \tag{7}$$

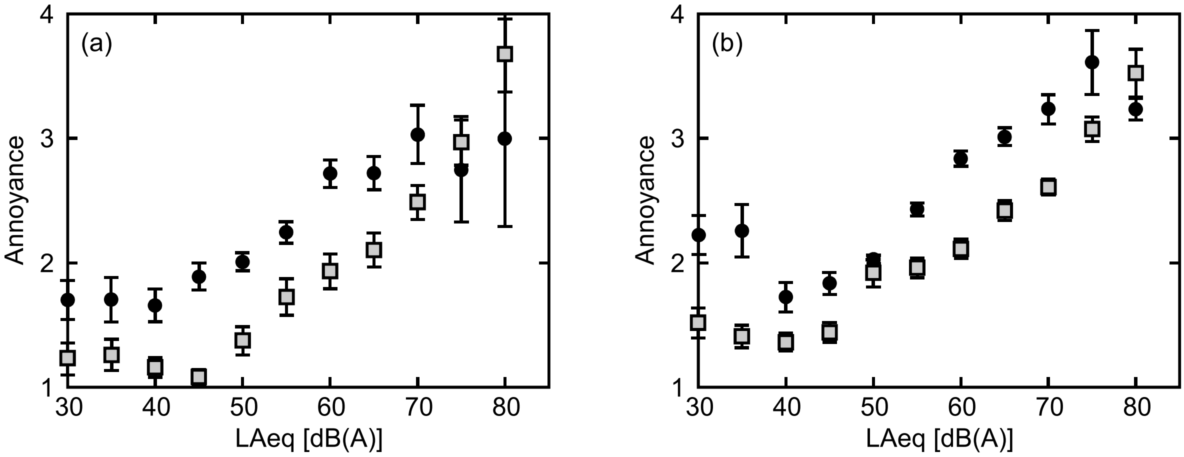

Figure 3 – Annoyance of road (●) and railway traffic (□) as a function of the computed average sound pressure level L_{Aeq}, for (a) the noise survey and (b) the simulation.

For the purpose of this paper, the complexity of the emotional and cognitive evaluation is reduced to the single variable A representing annoyance, which is assumed to be proportional to E. Also, important personal characteristics such as noise sensitivity are not used in the calculation example and hence not described in detail here.

Figure 2 shows an example of a measured indoor $L_{\mathrm{Aeq,1s}}$ time series, together with the detected events. The start of the time series shows that a notice-event is detected, which ends at about 425s due to habituation. The next notice-event at 500s is caused by a small peak in the intruding sound that is not blocked by any of the cited mechanisms. From 500s to 700s, the effect of habituation diminishes. The peaks around 650s are not detected because they are not high above the background level or the sound produced by the modeled individual itself.

3.2 Transportation noise

To validate the above described model, simulation results have to be compared with noise survey results. Since it is infeasible to record the noise exposure of survey participants during a sufficiently long period, their exposure to transportation noise too has to be simulated. Several sources of sound are modeled to capture the acoustic field: the noise caused by road and railway traffic, and the noise produced by the modeled individual itself (related to activity).

Because using noise mapping software to simulate the time-varying sound exposure would be computationally very intensive, it was chosen to use a simplified model for vehicle noise emission and propagation. It is assumed that the exposure of the modeled individual is mainly determined by the road and railway track closest to its location. Road traffic is modeled as a stream of vehicles, represented by omnidirectional moving point sources. Vehicle passages are assumed to occur according to a Poisson process. Trains are modeled as moving line sources. Propagation consists only of geometrical spreading; air absorption and ground effect are not accounted for. Finally, a building insulation factor has to be applied to calculate the exposure of the modeled individual whilst indoor.

3.3 Simulation results

The above described model has been implemented in an event-driven framework, using the Python programming language. Several aspects of the model have been tested on data obtained from a large scale transportation noise survey conducted in the Brennerpas [23], a mountainous region connecting Austria with Italy. Over 2000 people were interviewed over phone, and completed an elaborated questionnaire containing over 50 questions, part of which handling noise annoyance caused by road and railway traffic during the last 12 months.

The dwellings of the participants were geographically located using their address, and linked to the available GIS data. Subsequently, the distance of the dwelling to the nearest highway and high traffic flow road was determined. A 24-hour time series of $L_{\mathrm{Aeq,1s}}$ levels at the façade of the dwelling was simulated using the diurnal pattern of hourly traffic intensity on the particular roads, a Poisson process for vehicle passages, a gaussian distribution for the vehicle speed and source power, and a simple outdoor sound propagation model accounting for geometrical spreading. The same algorithm was applied to simulate an $L_{\mathrm{Aeq,1s}}$ time series of the train noise, originating from the main train track running through the area.

The modeled individuals in the simulation engaged in several activities, influencing their alertness, location and own generated noise. The daily activity pattern of each simulated individual was modeled using the distribution of survey responses about working status – (un)employed, retired or student – and a set of typical weekday activity patterns for the given categories.

Reported noise annoyance was simulated by two variables A_{road} and A_{train}. The retrospective process aggregated all annoyance caused by the particular source over the course of the simulated day using an additive process. Values below the median were interpreted as no annoyance

(0), and higher values were rescaled to the interval [1,5], to allow a more easy (visual) comparison of results between the noise survey and the simulations.

Figure 3 shows the reported and simulated annoyance as a function of the computed 24-hour average sound level $L_{\mathrm{Aeq,24h}}$. Both the simulation and the survey show a difference in annoyance between road and railway traffic noise, for the same average sound level. This difference, which is found in numerous noise surveys and laboratory experiments on transportation noise annoyance, is often called the *railway bonus* [1] – it is incorporated in the noise abatement legislation in several countries. The noise survey data (Figure 3 panel a) shows that, although initially, road traffic is experienced more annoyingly, the curve for railway traffic annoyance has a steeper slope, and for high exposure levels, trains are experienced as more annoying, or at least as equally annoying, as road traffic. The difference between road and railway noise is most important for mid-levels of noise exposure.

Looking at the simulated data (Figure 3 panel b), similar trends are found. The exact point of intersection of the road and railway curves is somewhat higher though. There is also a shift in the part of the figure where the difference is most important. Various reasons may be causing this. For instance, the computed $L_{\mathrm{Aeq,24h}}$ values may be shifted a bit differently for road and railway traffic, due to uncertainties about road traffic and railway traffic intensities. There may also be some cognitive effects playing a role in the long-term evaluation of the survey. One of the suggestions is that trains are perceived more environmental friendly, and are rated less annoying because of this. Nonetheless, the simulation results confirm to a large extent the observed difference between both sources of noise, without explicitly taking into account non-acoustic characteristics.

4 Conclusions and perspectives

A software agent approach to mimick the human response to environmental stressors has been outlined, containing submodels for sensory perception, cognition and emotion. The main goal of the model was to relate the observed modifying factors in environmental impact assessment to more fundamental physical, psychophysical and psychological principles, and thus, to reproduce and explain, in a qualitative way, trends and dependencies, observed in epidemiological research. This knowledge is a necessary step in the process of designing real world agents which are able to take intelligent decisions (e.g. closing windows) based on stressor input from the environment.

A concrete implementation, focused on auditory perception, has been presented. It was found that similar differences between effects of road and railway traffic noise on people are observed in the simulations with the proposed model as in experimental data, although the simulation did not have any prior knowledge about the source of noise.

Directions for the implementation of the cognitive and emotional submodels have been given. The conceptual model could be extended with a submodel for social interaction. Social interaction can play different roles. On the shorter timescale, social interactions may result in the spreading of opinions and the emergence of a common opinion. On the longer timescale, they help to shape the world view and expectations. As it is inconceivable that all personal interactions of a life time are modeled to come to a world view, a reference or expectation could be inserted into the model explicitly.

5 Acknowledgements

We would like to thank Peter Lercher (Department of Hygiene and Social Medicine, Medical University of Innsbruck) for supplying us the Brennerpas survey data, and Mats E. Nilsson and Birgitta Berglund (Gösta Ekman Laboratory for Sensory Research, Karolinska Institute and Stockholm University) for the many fruitful discussions on auditory perception.

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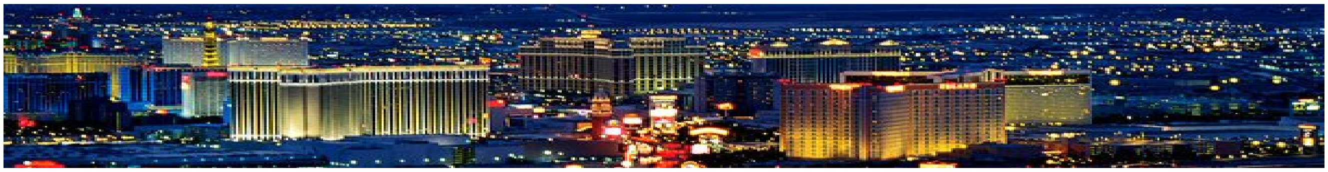

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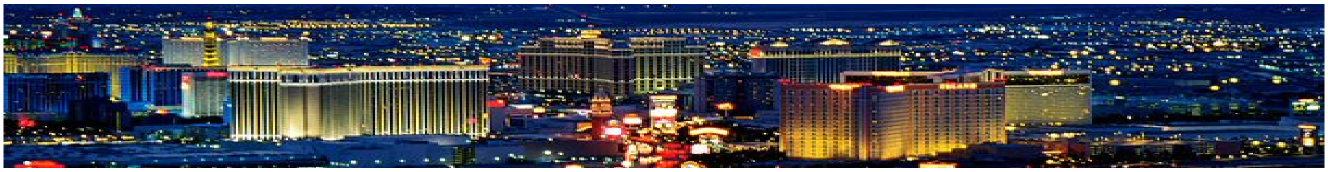

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University of Georgia
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ISBN: 1-60132-019-1

Produced by
UCMSS
San Diego, California, USA
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