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Applying capacity analyses to psychophysical evaluation of multisensory interactions

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ABSTRACT

Determining when, if, and how information from separate sensory channels has been combined is a fundamental goal of research on multisensory processing in the brain. This can be a particular challenge in psychophysical data, as there is no direct recording of neural output. The most common way to characterize multisensory interactions in behavioral data is to compare responses to multisensory stimulation with the race model, a model of parallel, independent processing constructed from the probability of responses to the two unisensory stimuli which make up the multisensory stimulus. If observed multisensory reaction times are faster than those predicted by the model, it is inferred that information from the two channels is being combined rather than processed independently. Recently, behavioral research has been published employing capacity analyses where comparisons between two conditions are carried out at the level of the integrated hazard function. Capacity analyses seem to be particularly appealing technique for evaluating multisensory functioning, as they describe relationships between conditions across the entire distribution curve, are relatively easy and intuitive to interpret. The current paper presents capacity analysis of a behavioral data set previously analyzed using the race model. While applications of capacity analyses are still somewhat limited due to their novelty, it is hoped that this exploration of capacity and race model analyses will encourage the use of this promising new technique both in multisensory research and other applicable fields.

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1. Introduction

The brain interfaces with the environment through many different sources of information. Waves of light and sound, the physical energy of vibrations and pressure, and chemical odorants and tastants provide different information about one's surroundings. In addition to clear benefits, this wealth of information provides the brain with distinct challenges of how, when, and if this information should be combined to best form a functional approximation of the surrounding world. Our experiences inform us that the brain has solved this problem to a useful enough degree, and research ranging from the moth to the human has demonstrated that interactions between the senses occur [1–5]. However, mathematical representations that provide the means to experimentally characterize the if and when of multisensory interactions remain a challenge. The present paper compares one of the most common methods of testing multisensory interactions in human psychophysical data, the race model [6] with the application of expanded survival analyses.

The race model is probably the most common method used for assessing human behavioral measures for evidence of multisensory integration. The race model, like all models, does have some limitations in its application and interpretation. First, the race model method is not always easy to briefly explain to those who are not familiar with it, as is often the case for neuroscientists or psychologists presenting findings to a broad audience. In addition, interpretation of the race model is limited by the fact that it is based on subtractions of cumulative distribution functions, which limits sensitivity and interpretation of results in the tails of the distribution. These concerns will be explained in more detail below. A method of comparing distributions based on survival analyses has been used recently to evaluate behavioral facilitation due to unisensory redundant targets [7] and differences between older and younger adults in a same/different task [8]. This capacity model takes advantage of hazard functions to not only address several of the limitations of the race model, but provide an intuitive output as well [9]. The purpose of this paper is to suggest the potential utility of integrated hazard functions and capacity analyses for evaluating multisensory processing, either by themselves or in combination with traditional race analyses. This paper is meant

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to facilitate practical application of capacity analyses rather than being an exhaustive treatment of the mathematical and theoretical concepts that underlie race model and capacity analyses, as these concepts have been addressed previously [7,10–12]. It is hoped that this discussion will raise awareness of these promising analysis techniques in the multisensory community and contribute to the evolving dialogue about defining and assessing multisensory interactions.

2. Methods

Data from a previously published study [13] were reanalyzed using capacity analyses. Basic information including subject characteristics, stimulus characteristics, and study design are included below and detailed in the original study.

2.1. Subjects

The study was intended to investigate the effects of normative aging on multisensory integration. Subjects underwent a thorough screening to evaluate their health, sensory acuity, and cognitive status. Data were collected from 31 healthy young adults (mean age = 28 ± 5.6 years, female = 16) and 27 healthy older adults (mean age = 71 ± 5.0 years, female = 16). All participants granted written, informed consent and were compensated for their time. All subject recruitment, informed consent, and data collection procedures were completed in accordance with the Wake Forest University School of Medicine Institutional Review Board and the Declaration of Helsinki.

2.2. Experimental set-up

All experiments were completed in a sound and light attenuated booth (Whisper Room, Morristown, TN, USA). Stimulus timing and presentation, and collection of reaction time and accuracy data were accomplished using E-prime software (Psychology Software Tools, Pittsburgh, PA, USA) and a serial response box. Visual stimuli were presented on a computer monitor and auditory stimuli through speakers flanking it. Volume was adjusted for each participant to a comfortable and easily discriminable level, typically around 75 dB.

2.3. Behavioral paradigm

Participants completed a two alternative forced choice task where they were asked to discriminate between the colors red and blue with a button press. Visual stimuli were red or blue filled, colored circles subtending 7.7° presented in the center of a computer monitor for 250 ms. Auditory stimuli were the words "red" or "blue" being spoken by a male voice and were 350 ms in duration. During each trial, participants could be presented with a visual target alone, auditory target alone, or a multisensory target (simultaneous presentation of visual and auditory stimuli). Multisensory targets were always congruent, that is, a red circle was never presented with the word "blue."

Each trial consisted of a 1s fixation period where a grey cross was presented in the center of a black computer screen. After the target was presented, the screen was cleared during the response period. The next trial was not presented until the participant responded or 8 s elapsed, at which point the next trial would begin. Subjects were instructed to respond "as rapidly and accurately as possible." Stimulus conditions were presented in pseudo-random order to limit stimulus order effects. Each condition, visual alone, auditory alone and multisensory, was presented 44 times over the course of the experiment. Participants were highly accurate on this task (younger mean accuracy = 42.7 ± 1, older mean accuracy = 43.0 ± 0.9). Inaccurate responses were not included in analyses. Response times were effectively cut off at 8 s, as noted above, and responses faster than 250 ms were excluded from further analysis. Results from redundant multisensory targets are presented in this manuscript. Cumulative distribution functions from visual and auditory trials are not illustrated, but were used to calculate race models and capacity curves.

3. Discussion of analyses

3.1. Modeling multisensory interactions: the race model

Data from extracellular neural recordings in animals and reaction time and accuracy experiments in humans show that the presence of multisensory stimulation results in gains in the form of increased neuronal firing, faster reaction times or improved accuracy under certain circumstances [14–21]. Such gains are examples of a positive interaction or dependency between the sensory channels, where more information results in better performance of the system. Sensory inputs can also be dependent on one another in a negative way, where the presence of information from additional sensory channels actually interferes with behavioral functioning or depresses the firing of neurons [22–24]. Of course, it is possible that in some situations the senses do not interact at all, but are processed fully in parallel, independent streams. Parallel, independent models are referred to as race models, because under these conditions, responses to the environment are determined by whichever input is processed the fastest [6,11,25,26].

The race model distribution in multisensory literature is the predicted response time distribution to multisensory stimulation that would be observed if information from different sensory channels were processed separately [6]. That is, it illustrates the distribution that would result if two channels of information were processed simultaneously, but there were no interaction or convergence between the channels. Under these conditions, multisensory processing is a "horse race" where the signal that reaches threshold first is the one that determines behavior. The race model distribution is generally calculated by summing the observed responses to individual sensory channels. Because the race distribution is a minimum distribution made of the fastest responses, it is typically faster than either unisensory distribution. The speeding of responses due simply to the fact that two sources of information are present is termed statistical facilitation [25]. Very generally, the race model posits that if observed responses are faster than the responses predicted by parallel processing (e.g., speeding due to statistical facilitation), it can be inferred that interaction between the sensory channels has occurred. More thorough treatments of the influence of stochastic and context invariance and different models of processing architecture and decision rules have been previously published [7,11,12,27,28]

3.2. Computing the race model

A typical multisensory experiment using the race model has at least three conditions: presentation of a target in one sensory modality, presentation of a target in another modality, and presentation of both modalities simultaneously. The race model distribution is calculated by summing the cumulative distribution functions (CDFs) of observed responses to the two unisensory conditions to create a predicted multisensory distribution. Each value in the CDF reflects the cumulative probability of a response occurring at a given range of reaction times, e.g., 240–250 ms. The probability for response can then be compared between the race