Dynamic Perspective on Contextual Effects of Visual and Auditory Perception A psychophisical Study

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Contents

Abstract

This is a psychophysical study which relates to the gap between a physical stimulus and the subjective perceptual experience it evokes. It is concentrating on the issue of fluctuations in perception of weak stimuli in the visual and the auditory modalities. Fluctuations mean that repeated presentations of the same input level, on the detection threshold, result in different responses. Streams of these responses are characterized by structural features and functional regularities which imply that these fluctuations are not low-level noise but are connected to cognitive processes.

In this study we specifically inspect the dynamic properties of these responses. The dynamic perspective and, accordingly, experimental design in this work are not conventional. Unique methodologies of analysis were developed and adapted to match the dynamic properties of interestm while the limitations of these methodologies were also considered. We approached the dynamics in two ways – a) directly- by manipulating input temporal structure and b) indirectly by inspecting the linkage between perception processes of audition and vision.

In order to investigate the temporal context in which the stimuli are presented, we have chosen to refer to the changes in the input amplitude around the sensing threshold. We presented three structures which differ in their level of internal correlations: no correlation, correlated and highly correlated. These structures, which were chosen to resemble different natural rhythms, enabled us to evaluate general concepts; We showed that opposing tendencies take effect over different timescales, with a different balance between the tendencies emerging in each of the regimes, which enabled us to explain the complex structure of any of the response streams. A general manifestation of this balance was formulated into a mathematical model which described well the experimental results in all regimes.

The indirect method revealed some of the complex relations between responses of the two modalities. Although in our experiment auditory and visual stimuli were not bound to a single object, nor they were presented simultaneously, still their responses were linked in their dynamical properties. The specific linkage is dependent on the contextual relations of both modalities with the perceived object. Contextual relations were controlled via a "response clamp" which is a closed loop procedure including ongoing adjustment of the input level reacting to the history of responses. The cross-

modal influence was asymmetric, as clamping just the auditory fluctuations was also effected by quenching the visual fluctuations, but this was not the case the other way round.

We have also showed that the properties of perception of a single modality can alter when more modalities are involved. This emphasizes the need to relate to all the contexts in which perception processes are measured, and to the manner in which they are analyzed and interpreted.

In general, the study supports the view that the dynamics of response fluctuations are related to cognitive processes. We demonstrated the importance of relating to temporal and other contexts in psychophysical measurements and in their interpretations. The novel dynamic point of view also contributed to developing new methods that allow the relations between stimulus, response and context to be examined over various timescales.

Chapter 1

Introduction

Perception of weak stimuli tends to be unstable: fluctuations are found in the responses to repetitive trials of such stimuli. These fluctuations have been addressed in many previous psychophysical studies. Sometimes, the unstable nature of responses was considered as a noise or a problem to be overcome, e.g. in estimating perceptual thresholds. This has led to the development of various methods trying to average out fluctuations in order to characterize the overall properties [6, 13, 65]. On the other hand, some previous studies focused on the fluctuations themselves [26, 33]. These are also the main topic of the current work.

The motivation for examining response fluctuations is the hypothesis that they do not reflect "just noise" but some interesting psychophysical phenomena. Specifically, fluctuations may be linked to higher mental functions that are reflected in perception. Support for this linkage comes from both temporal characteristics of these fluctuations and their functional relations with other processes. Temporally, response fluctuations carry a fair amount of internal correlations over various timescales [73, 68]. These correlations have been characterized as $\frac{1}{f}$ noise, which is often found in natural signals [70].

Functionally, *contextual effects* can evoke regularities in a way that could generate what appears to be fluctuations when related only to the momentary input signal. The average of instantaneous input-output relations over an entire experiment is called a psychometric curve. Significant context effects were found by manipulating overall input content, which resulted with a modification of the psychometric curve [76, 62, 48].For example, the range of input signals modulates the psychometric curve, so that the dynamic range of the curve is adjusted to the input content. Other examples are the "anchor effect" and the "frequency effect" that represent different ways by which responses tend to center according to stimulus range or prevalence, respectively [57, 47]. All these effects refer to the global statistical structure of the stimulus, and can be interpreted as an adaptive property that utilizes a limited dynamic range to maximize its correspondence to signal statistics. For example, in sensory neural systems, such modification of the input-output function was directly linked to maximizing information transmission [8].

Temporal context and past history also influence present perception. These manifest as tendencies to respond in a certain manner depending on inputs rather than the current instantaneous one. In detection tasks that involve feedback on performance, one may interpret history-dependence as a form of short-term learning from experience [1]. However, past history affects perception even without such feedback. Previous studies have found that there are both positive and negative effects with respect to previously encountered stimuli and previous responses [28].

Negative effects induce bias towards a signal opposite or different from the previous ones. Such effects are prominent after exposure to a sustained or strong sensation. Perception is then biased to overshoot the estimation of a new stimulus to the counter direction of the preceding one [29, 10]. The effect is also known as a "negative after effect". This effect is thought to contribute to maintaining sensitivity to new information and to the detection of changes [11].

A *positive* effect refers to the tendency to repeat previous responses, or to estimate signals as similar to those previously perceived [46, 37, 3, 14, 58, 33]. Such effects are predominant when stimuli are very weak; it was found that responses to stimuli near the perceptual threshold display a "positive recency" - trial-to-trial positive correlation [46, 37, 3]. This effect is thought to stabilize perception of stimuli near to the threshold against noise and ambiguity [58].

In addition to these considerations, some studies used functional brain imaging and found that perception fluctuations matched specific features of EEG waves which presumably reflect certain mental states [42, 9, 45]. Similar results were demonstrated also using fMRI [67, 45]. Additional support for connecting fluctuations to high mental functions was found in the relations between the fluctuations in different modalities [22]. All these findings connect the fluctuations to central processes and imply that they are not just a collateral noise emerging from the sensory path. This conclusion raises the question what they functions actually reflect and what are the core processes that generate them.

This study is aimed to characterize fluctuations in the perception of weak stimuli, and accordingly to reveal possible interpretations for their origin. In particular, we focus on the influence of context - temporal and cross-modal - on perception. A unique feature of this study is that the experiments are designed and analyzed using a *dynamic* perspective. In practice, the dynamic approach is implemented using one general principle: the continuing sequence of inputs and outputs are regarded as ongoing signals that relate to one another. This contrasts with the commonly used static approach, in which each individual output relates to an instantaneous input signal.

The majority of studies on temporal history inspected each stimulus with respect to one or two previous inputs [14, 47, 51] or to the previous response [46] which is insufficient for estimating processes of different time scales. Many used a priming stimulus presented before each trial to control the previous experience [25, 58]; such priming in fact restricts the consideration of the influence of a longer history.

In at least one case where the effect of longer histories on perception was considered, the interpretation of the results elicited a debate in the literature [10, 39, 33]. This debate highlighted the need for an experimental methodology by which influence of history could be tested. In this study we aim to evaluate the influence of a longer temporal history by structuring all stream of input stimuli. This approach allows the effect of history on perception to be examined, over many timescales, without disrupting the continuous presentation of stimuli.

In this thesis the dynamic inspection of fluctuations is divided into two different approaches. The first is a direct approach, in which we focus on the dependence of response on *temporal* context. The second approach is less straight forward: there, we use closed loop experiments to reveal dynamic relations *between modalities* and between the subject and the perceived object for uncovering hidden processes underlying the fluctuations.

To elaborate: In the direct method we measure and formulate the reliance of a response on previous streams of inputs and responses. In traditional psychophysical experiment design, signals are presented in a random uncorrelated sequence [31, 14, 71, 20, 28]. One might have hoped that such a presentation would minimize response bias, but in fact the first descriptions of trial-to-trial effects came from such experiments [68, 6, 49, 40, 71]. Interestingly, this uncorrelated order was also used in studies estimating biases and temporal context effects themselves [31, 14, 71, 20, 28]. It is now known that under such stimulus regimes, responses exhibit slow fluctuations and internal correlations [68, 73, 30, 38].

In this study, we explore how sensory detection combines with history-dependent biases over multiple timescales. In such investigations it is crucial to manipulate the input signals so that they have various temporal structures. Such manipulations allow history-dependence of the input signal to be distinguished from the history-dependence inherent to human observers. We aimed to study spatial visual detection based on time-dependent sequences spanning regimes that carry a controlled amount of internal correlations. At one extreme the signal is entirely uncorrelated, the other extreme is characterized by very slowly varying signals, with the intermediate regime also having been investigated. In addition to providing an experimental control for the involved timescale, this construction will also bring the experiments closer to real-life situations: most natural experiences have strong correlations, temporal and others [74]. Indeed, various biological systems have been shown to exhibit a preference for correlated signals, in the sense of a more effective representation and response. This has been demonstrated at the level of a single neuron [27], in cortical networks [36, 15, 69], in sensory neural coding [75] and in cognitive processes [74, 53, 56].

Our results show that sequences of responses have both positive and negative biases, but these tendencies have different characteristic timescales. In the short term, responses are biased to be similar to previous ones. This effect is manifested, for example, by a probability of response alternation (POA) which is lower than a random sequence of independent detection events, for all types of input signals. In the long term, by contrast, there is an opposing bias moving away from the trend of responses that represent a longer timescale history. This tendency can be seen as an exploratory force, and its presence is emphasized when the stimulus varies slowly. These two opposing biases are manifested by a hysteresis of the psychometric curve which changes sign from positive hysteresis over short times to negative hysteresis over longer times. In each of the stimulus regimes structures, the interplay between these effects and the timescale of the input signal results in a psychometric curve with markedly different slope.

A model of perception composed of two stages is presented: a sensory stage, where the input signal is estimated; and a cognitive stage, where a decision is made. By making both stages amenable to modification by history-dependent processes we were able to capture the entire set of experimental observations.

In the second part of this work we study response fluctuations characteristics by an experiment that aims to expose the linkage between auditory and visual modalities. The inter-modal relations have been thoroughly studied from a static point of view, with different types of interactions between them having been documented. Global measures such as response times were demonstrated to be affected by cues of other modalities [24], and coordination between slopes was found between auditory and visual psychometric curves in level matching paradigms [61]. Interference is a well-known type of interaction between modalities, which can be interpreted as sharing a limited common resource such as attention [66, 64, 34, 35, 2]. On the other side sometimes the interaction is constructive, where the modalities support each other's perception. A famous example of this is the McGurk effect (hearing speech when seeing the talkers face improves perception of words as compared to listening without the visual aid) [41]. Such relations beteen the modalities are well suited to being examined from a dynamic point of view since they are related to attention, which is by essence a dynamic process. Therefore, for these specific claims, the dynamic approach is the heart of the matter.

Some attention related studies which refer to cross-modality interactions enforce or control specific attention states during the experiments [50, 21]. The purpose is obviously to minimize variability and reach coherent results. However, such methodology conflicts with the dynamic, voluntary and partially unconscious nature of attention. Therefore, in this study, we analyzed perception as a dynamic process, letting attention be free and voluntary, while adjusting the experimental and analytical methods accordingly.

Moreover, in many dual-modal experiments, mainly those which deal with the attentional load, the static approach dictates simultaneous presentation of stimuli [61, 19, 7, 59]. Unfortunately, this may cause various factors, including object binding, to be mixed with the results [23, 55, 52]. In the dynamic approach we are not limited to using a concomitant presentation. We present consecutive stimuli where each time only one (unexpected) modality may be presented. Using extrapolation and alignment of the modalities signals we are able to continually track temporal relations between them.

In order to characterize the fluctuations' relations in the two modalitied, we use different regimes of interactions with the perceived objects. The interactions with the objects are implemented using a controller that operates a closed loop procedure. The idea in the method is that instead of analyzing "wild fluctuations" we control them, "clamp" them, and inspect the parameters of the controller used for the procedure. This is an accepted method in the field of membrane potential and also in neuronal spiking studies [? ?]. In the current study, however, instead of voltage or spike response clamps we apply the clamp on psychophysical responses. The principle of controlling variability is that each response is used for the adjustment of upcoming stimuli: if the current detection was easy for the subject then the next stimulus will be harder, and vice versa. The usage of such mechanisms for the study of response fluctuation in psychophysical experiments is relatively new; it was presented in this framework for the visual perception in Marom & Wallach paper from in 2011 [38].

In the current study we clamp response fluctuations of each modality separately. In the different sessions we clamp either modality or both modalities (with two controllers) and compare the temporal relations to those of an open loop session. This enable us to separate influence of each modality's relations with the object with the other modality's fluctuations.

Using this indirect path to study fluctuations in response, we find that some global dynamic properties of the fluctuations indeed interact between the modalities. The influence is not reciprocal, visual fluctuations are more influenced by the auditory than the other way round. An additional aspect of relations is related to their temporal synchronicity. While closed loops bind and synchronize the modalities' fluctuations together, in open loops they exhibit the opposite tendency - they are counter correlated. The counter relations can be interpreted as competition on a common resource, presumably attention.

Chapter 2

Visual experiment - Temporal structure

2.1 Methods

2.1.1 Experiment Procedure

2.1.1.1 General

A Visual experiment was conducted in order to estimate temporal structure and contextual effects on perception. Consecutive visual stimuli were presented under various temporal structure profiles. In all profiles stimuli were presented in various levels of perceptual difficulty. Difficulty raised because stimulus was a circular spot similar to the background, whereas the subject was required to supply a dichotomous response. In each trial the subject was requested to report whether there was a spot or not. In practice there was always a spot, only sometimes the contrast between the objetcs and the background was very low

In the experiment participated 18 subjects aged 23-31, 9 females and 9 males. They had regular or corrected to regular vision and were not diagnosed as having attention deficit disorders. 2 female subjects were excluded from results for having extremely high positive responses ($> 40\%$) for trials of very low input levels, which implied credibility problems.The experiments were conducted in a dark room where subjects sat alone in front of a computer screen. All subjects were naive to the purpose of the experiment. Subjects signed a consent form and were paid for their time.

2.1.1.2 Stimulus and Trial structure

A stimulus was a circular darker spot on a noisy background (see middle panel in figure 2.1).

The background is a static image of "white noise", that is, randomly distributed black & white dots (500X500 pixels). This is a darker circle (60 pixels diameter) appears in a fixed radius (150 pixels) from the center, at a random angle. Black and white dots were independent and identically distributed (i.i.d.). All background pixels had probability of 0.5 to be either black or white, in all trials of all sessions. A new background with same statistics was generated for each trial.

The spot (diameter 60 pixels) was also composed of i.i.d. black and white dots, but the probability of being black changed from trial to trial. Spot probability was higher than 0.5 making the spot always darker than the background. The angular location of the spot on the background was randomly changed from trial to trial: the angle was randomly raffled while the radius was fixed (150 pixels from the center).

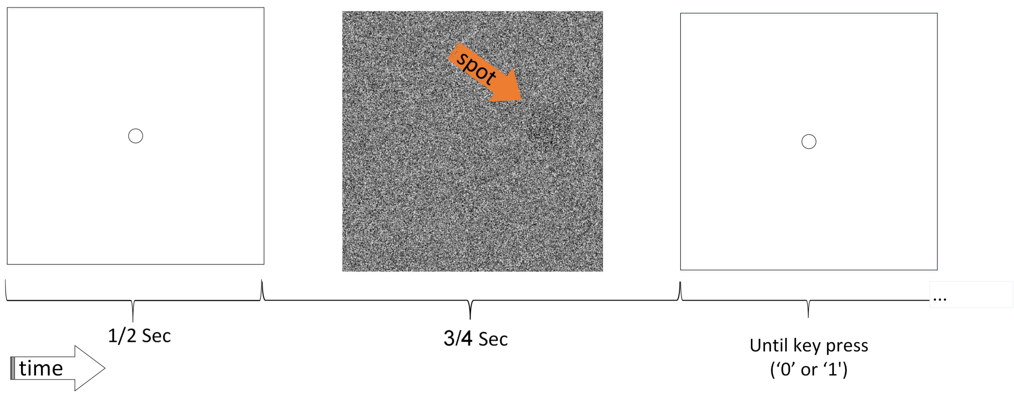


Figure 2.1: a **Stimulus trial** starts with a blank rectangle with a fixation circle. After 500ms the stimulus appears for 750ms, then the blank screen returns and stays until the subject reports whether he noticed a spot or not.
Spot in this example has input level of 0.6 (probability of balc pixels). Spot location is pointed for illustration purpose with an orange arrow.

Each trial began with visual reset period of 500ms long, in which a white screen with a fixation circle in the center was presented. Then, the stimulus was presented for 750ms, after which the white screen returned (figure 2.1).

The subject was instructed to report with a key-press if there was a spot or only background, pressing '1' or '0' respectively. Pressing the response key initialized the next trial. The experiment was self-paced since responding had no upper time limit. Responses were accepted also if subject had responded during stimulus presentation, but the time of presentation was not shortened upon.

In the example given in figure 2.1 the probability of a spot pixel to be black was 0.6. From here on the term "level" refers to the probability of spot pixels to be black. This level, 0.6, is within the dynamic range for most subjects, in other words: if this stimulus level were presented several times to a subject, it would be detected at least some of the times. The minimal level was 0.5, meaning that there was no spot at all since the statistics of background and stimulus were the same. As the input level got higher the spot appears above the background more easily.

2.1.1.3 Manipulating of temporal structure of input levels

Each experiment included 3 sessions, each composed of a sequence of stimuli with different temporal correlations.

The distribution of input levels was always normal with same mean and same standard deviation (STD) across all experiment sessions. The difference between experiment sessions was only the *order* of stimulus levels presentation.

In session "White" input levels were generated in consecutively independent manner, so input levels vector presented memory-less "white noise". In session "Pink" it was consecutively correlated creating $\frac{1}{f}$ noise and in "Brown" it was even more correlated creating $\frac{1}{f^2}$ noise.

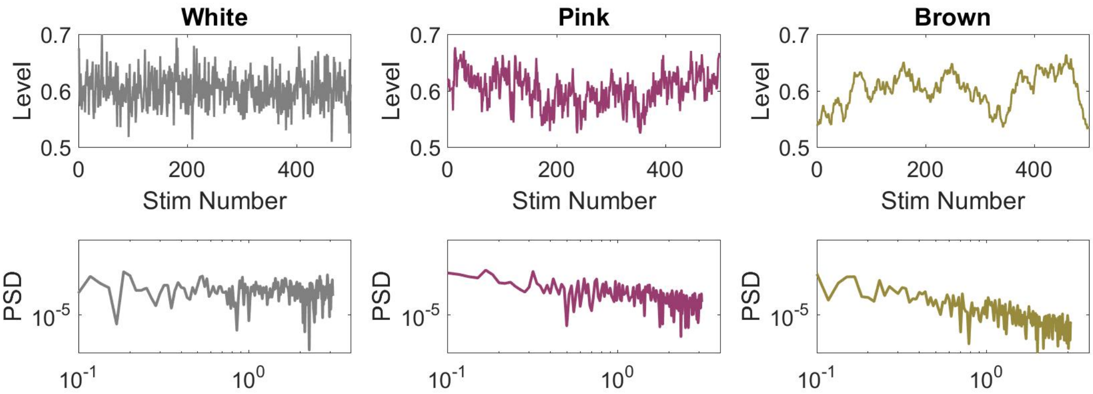


Figure 2.2: **Experiment sessions** Example from subject DM_F_24. Each session has 500 trials, upper panels show levels in their temporal order, lower panels show power spectral density (PSD) of the corresponding session. On the left "White" session (trace color is grey) consecutive inputs are not correlated and clearly the PSD it is flat. Central panel "Pink" session (trace color is pink) consecutive inputs are correlated and the PSD is descending. Right panel "Brown" session (trace color is yellowish-brown) consecutive inputs are highly correlated and the PSD is sharply descending.

2.1.1.4 Experiment Structure

The visual experiment consisted of 3 main sessions with 2 additional control sessions, conducted before and after main sessions (figure 2.3). In each session there were 500 consecutive trials of visual stimulus. The 3 sessions were presented to each subject in a random order.
Control sessions had only 100 trials.

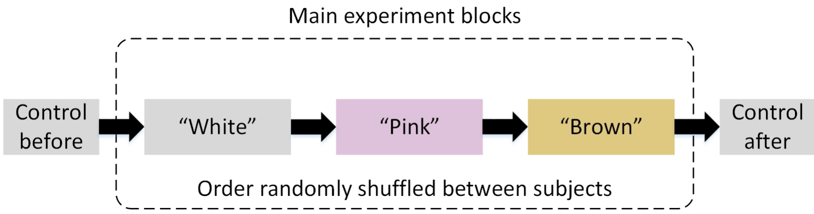


Figure 2.3: **Experiment structure**

2.1.1.5 Determination of input statistics of a subject

For each subjects first a control session was used to appraise individual parameters. Control sessions consisted of 100 trials, input levels were consecutively uncorrelated ("White"). The distribution of levels was normal, in control sessions it was always with mean of 0.595 and STD of 0.0297, which is 5% of the mean.

Analysis of the first control session determined the individual mean and STD which will be used across all main sessions for this subject. The mean was set to the be at the threshold, i.e. the crossing level of 50% detection rate. STD was 5% of it.

2.1.2 Technical Details

2.1.2.1 Extracting psychometric curve parameters

A Psychometric curve is referred to the relation between input level and the subjects actual detection rate in this level. Detection rate was calculated for level in bins of 0.075 width (figure 2.4). A continuous curve of detection probability (DP) for all input levels was estimated from these points using a weighted curve fitting procedure. The fit was to a sigmoid function spanning between 0 to 1, represented by the formula:

$$Sigm(x, Sl., Th.) \equiv \frac{1}{1 + 10^{Sl.*(x-Th.)}} \tag{2.1}$$

Where x is the input level and the parameters $Sl.$ and $Th.$ are the slope and the threshold, respectively.

The weighing, giving different significance of each point, was dependent on the sample size from which each point was derived. The fitting process, which was designed to find the slope and threshold ,was iterative using *Matlab* function for nonlinear fit - nlinfit.m

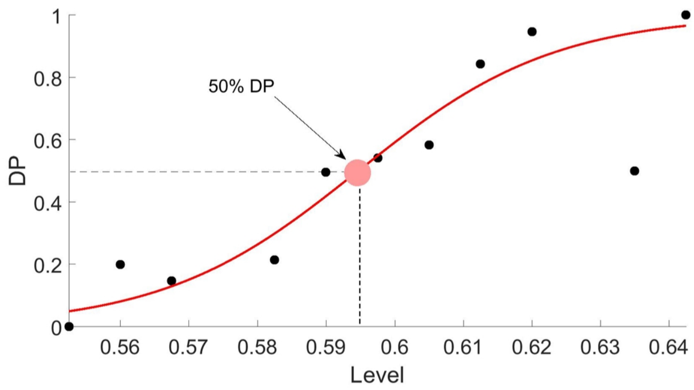


Figure 2.4: **Psychometric curve parameters** Level of crossing 0.5 DP (detction proabability) is the threshold *Th.*, and the steepness of the curve is represented by the slope *Sl.*, as defined in equation 2.1

2.1.2.2 Paradigm Validation - the task involves no learning

Comparison between "Before" and "After" control sessions was used in order to verify that no learning process was involved in the experiment. Three parameters of performance were compared, all of them showed no significant change.

Comparison parameters are: a) *Th.* - Threshold of the psychometric curve, b) *Sl.* - Slope of psychometric curve and c) *Total detection rate* - the number of detentions out of the 100 trails.

As seen in figure 2.5 there is no significant change between "Before" and "After" experiment sessions in all three parameters.

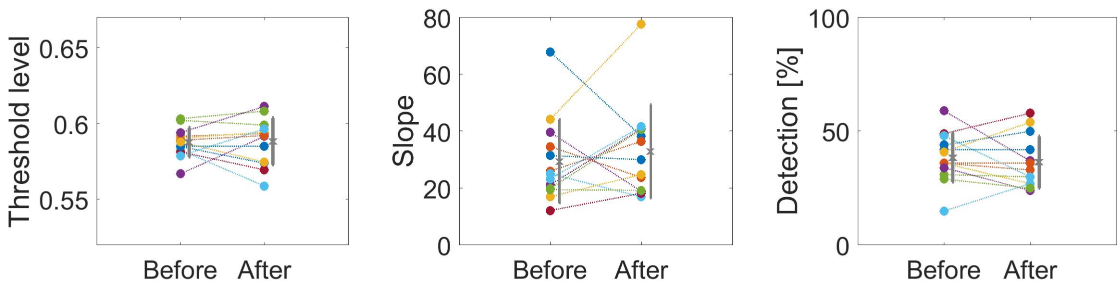


Figure 2.5: **Performance comparison before & after experiment** Each colored circle represents a different subject, errorbars marking mean and standard deviation (STD) across subjects. No significant change in any parameter.

2.1.2.3 Analysis of hysteresis conditioned upon the history of input

For conditioning the results upon input history we calculated the hysteresis between psychometric curves of the two conditions. Input history is represented by a filtered version of the inputs calculated as follows:

$$F(x_n) = x_n * (1 - e^{-\frac{1}{\tau}}) + F(x_{n-1}) * (e^{-\frac{1}{\tau}}) \tag{2.2}$$

Each component n of the filtered signal was classified according to the derivative sign $\delta F(x_n)$: labeled "up" if the derivative of the filtered signal was positive (level increased) and "down" if it was negative (level decreased).

$$\delta F(x_n) = F(x_n) - F(x_{n-1}) \tag{2.3a}$$

$$n \in \begin{cases} up & if \quad \delta F(x_n) \geq 0 \\ down & if \quad \delta F(x_n) < 0 \end{cases} \tag{2.3b}$$

Parameter τ in equation 2.2 determined how far back the history of inputs counted in defining the trend; As the filter became longer, with higher τ values, the "up"/"down" relied to a more general trend of the input signal.

2.1.2.4 Sensory-Cognitive Model details and constants

A model of perception composed of two stages is presented: a sensory stage, where the input signal is estimated; and a cognitive stage, where a decision is made. All blocks and equations of the model are defined hereby in details:

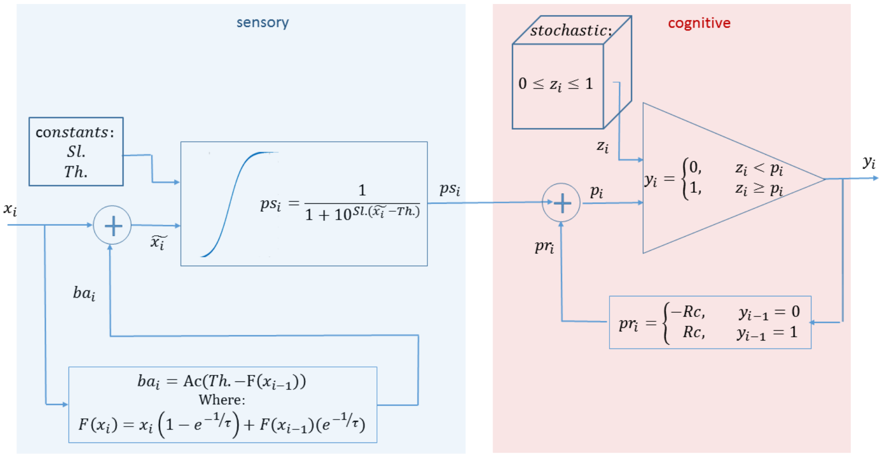


Figure 2.6: **Sensory-Cognitive detailed model - dependent on history of inputs and responses**
The sensory process (blue box) - is modeled by instantaneous sigmoid relations between the input level $\tilde{x}$ and ps the probability of response to be 1. Adaptation is modeled by biasing the physical instantaneous input level x by adding ba to it, which results with the effective input $\tilde{x}$. The value of ba is based on the *history of inputs*. Specifically ba depends linearly on the distance between the input level and the threshold.
The cognitive process (red box)- is modeled by a comparator that digitizes the response according to a stochastic process; A number z between 0 and 1 is raffled from a uniform distribution and compared to an effective probability p of the response to be '1'. p is the summation of the sensory probability ps with the recency effects pr. pr is a constant probability Rc which is added or subtracted, dependent on the *last response*

1. **Adaptation Bias of Input -** ba - is a linear "spring" which acts to balance history towards the central value of the threshold $Th.$ (equation 2.4a). History $F(x)$ is represented by filtered value of previous inputs. The filter is an exponentially decreasing filter, which means that the recent inputs have more influence than the further ones (equation 2.4b). The decay of the filter is characterized by a constant τ. In the model $\tau = 24$ [*time steps*].

   The bias grows linearly with the distance between the filtered history and the threshold. The distance between threshold $Th.$ and history $F(x)$ is multiplied by a constant Ac (equation 2.4). In the model $Ac = 0.25$ [*probability multiplier*].

2. **Effective Input Level -** $\tilde{x}$- is summation of the pysical input level x and the bias resulting from the adaptation (equation 2.5). $\tilde{x}$ can be higher or lower than the physical x since adaptation bias can be either positive or negative. For example: if recent history of contained many high levels the $F(x)$ is higher than threshold $Th.$, therefore the delta $(Th. - F(x))$ is negative, and the adaptation bias will decrease physical input level x such that $\tilde{x} < x$.

3. **Sensory Probability -** ps - is calculated for each input level using a sigmoid function of fixed parameters: $Sl.$ & $Th.$ which represents the Slope and Threshold

respectively (equation 2.6). The parameters *Sl.* & *Th.* that were used in the model were the average parameters found to characterize the human subjects. Specifically *Sl.*=30, *Th.*=0.595.

4. **Stochastic Response -** z - is a number between 0 and 1 which is raffled every trial from a uniform distribution. z is then compared to the effective probability p for response to be '1'. The result of this comparison is the binary value of the response y (equation 2.9).

5. **Recency Bias of Probability -** pr - is dependent only on the previous vote. A constant Rc is added if the previous vote was '1' and decreased in case it was '0' (equation 2.7).
   In the model $Rc = 0.1$.

6. **Effective probability -** p- is the sum of the sensory probability ps and the bias probability pr resulting from the recency effect (equation 2.8).

$$ba_i = Ac * (Th. - F(x_{i-1})) \tag{2.4a}$$

$$F(x)_i = x_i * (1 - e^{\frac{1}{\tau}}) + F(x_{i-1}) * (e^{\frac{1}{\tau}}) \tag{2.4b}$$

$$\tilde{x_i} = x_i + ba_i \tag{2.5}$$

$$ps_i = \frac{1}{1 + 10^{Sl.*(\tilde{x_i} - Th.)}} \tag{2.6}$$

$$pr_i = \begin{cases} Rc & if \quad y_{i-1} = 1 \\ -Rc & if \quad y_{i-1} = 0 \end{cases} \tag{2.7}$$

$$p_i(y_i = 1 \mid x_i, \, y_{i-1}, \, F(x_{i-1})) = ps_i + pr_i \tag{2.8}$$

$$y_i = \begin{cases} 0 & if \quad z_i < p_i \\ 1 & if \quad z_i \geqslant p_i \end{cases} \tag{2.9}$$

2.2 Results

We characterize the responses behavior in 4 ways of analysis: The first relates to the over all psychometric curve characteristics. In the second way the recency effect is being evaluated. The 2 last ways of analysis refer to conditioning of the responses upon inputs and outputs, respectively.

2.2.1 Sharper psychometric curves for slowly varying inputs

We first characterized the observers' performance to the different temporal signals by estimating the psychometric curve for each of them. The psychometric curve represents the response to the momentary input level, averaged over the entire experiment. Figure 2.7a shows an example of the three psychometric curves computed for one observer for the three different stimulus regimes. It can be clearly seen that the curve is most shallow for the "White" stimulus, where input levels are presented independently at each trial. The curve becomes sharper for the "Pink" stimulus with temporal correlations, and is *sharpest* for the "Brown" stimulus which varies most slowly. Sigmoidal fits to the data points are shown in solid lines; these fits define two parameteres for comparison among observers: *Sl.* and a *Th.*. These were extracted for all experiments by the procedure described in 2.1.2.1.

The slopes for all observers are shown in figure 2.7b, where the average is seen to increase with the signal correlation: on average over all observers,

$$Sl._{White} \leq Sl._{Pink} \leq Sl._{Brown} \tag{2.10}$$

Since variability between subjects was higher than between averages of different sessions, the individual slope for the white-stimulus session was subtracted from of those of the correlated sessions, pink and brown, for each individual separately. The result shows with high significance that the per-subject slope of the psychometric curve in response to white-stimulus is lower than that of pink or brown, as seen in figure 2.7c.

The threshold values *Th.* of the psychometric curve, in contrast, showed no consistent change between stimuli of different temporal structure (figure A.1 in Appendix A.1.1). Consistently with this observation, the total detection probability of any given observer did not change systematically among the different stimulus regimes.

The significant dependence of the detection slope on temporal stimulus properties provide the first solid evidence for history-dependence in detection. Since the different stimuli display the same overall distribution of input levels (see Methods), a strictly static response would result in the same psychometric curve for all of them. This is because characterization by a psychometric curve disregards temporal structure altogether shuffling the inputs (and corresponding outputs) randomly in time for any given experiment does not change the psychometric curve. Therefore the different curves clearly show that additional variables related to the sequence of presentation determine perception; to expose these variables it is necessary to consider the temporal sequence of responses and corresponding inputs.

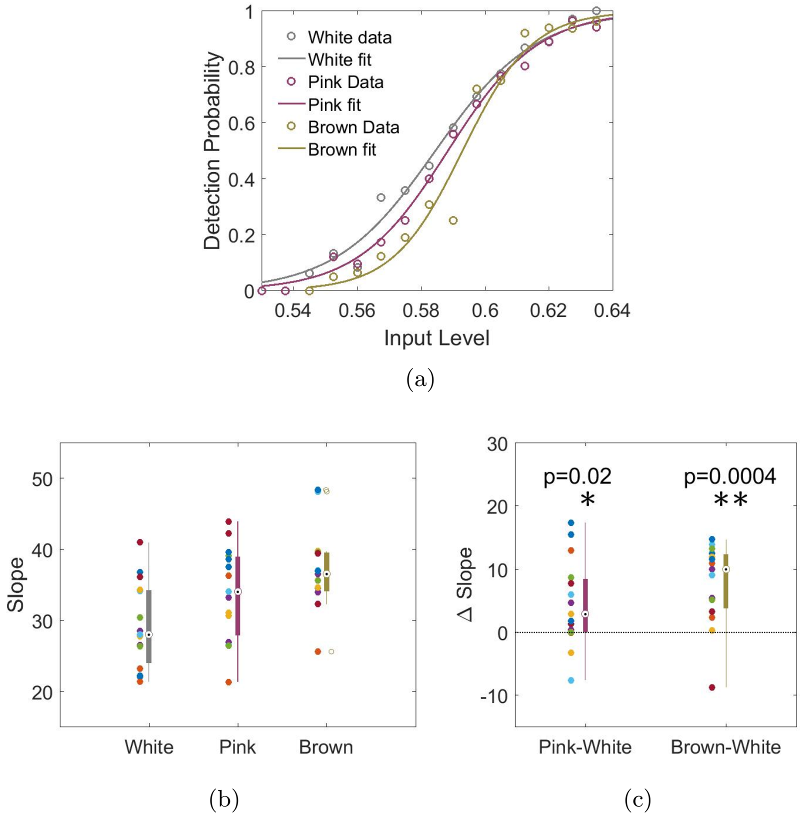


Figure 2.7: **Slope of psychometric curve depends on input temporal structure**. (a) Example of psychometric curve for a single subject IR_F_23. Circles: binned detection probability, lines: fitted sigmoid. Color code marked in legend. (b) Estimated slopes of psychometric curves for all subjects (each colored circle is an individual). On average, the slope increases for more slowly varying input signals: $29.3 \pm 2.5 \quad 32.8 \pm 4.2 \quad 36.5 \pm 2.7$ for White, Pink and Brown respectively. Errorbars mark the standard deviation (STD) across subjects. (c) Individual slopes relative to White session: Slope estimated for White signal is subtracted from slopes of the other signals for each subject individually. Differences between sessions within every subject are significant across subjects. Statistical T-test performed, significant changes are marked with asterisks with p-values noted.

2.2.2 Probability of alternating responses is lower than chance in all stimulus regimes

In many perceptual detection tasks, a "positive recency" effect occurs: the response to a stimulus presented at a given time is biased towards the response in the previous presentation. This result is well known in psychophysics settings of uncorrelated signal presentation (review in [20]). A quantity which measures the magnitude of this effect in binary responses is the probability of alternation (POA), defined as the fraction of reversals in a binary string:

$$POA \equiv \frac{number\ of\ alternations}{number\ of\ trials - 1} \tag{2.11}$$

Where *'Number of alternations'* means the number of changes, between any one type of response and the other, in both directions. For a random, symmetric uncorrelated binary string, POA is expected to be 0.5; lower values correspond to strings with longer streaks, or less alternation.

In our experiment the number of alternations is affected also by the input signal. If the input is slowly varying it has extended below or -above-threshold regimes and this will result with in long streaks of '0' or '1's, respectively. Therefore POA is expected to be lower for the more slowly varying inputs even for a static observer with no biases, reflecting a property of the input itself. In order to distinguish this input-dependent effect from possible bias and history-dependence of the observers, we use the psychometric curves computed above and simulate artificial "instantaneous" observers who draw their response probabilistically based only on the momentary value of the stimulus and the psychometric curve. The instantaneous model (in figure 2.8) is based on the sigmoidal relations between input level and response as defined by the transference function in equation 2.1). For each stimulus type we used sigmoid responses with the corresponding slope found in 2.2.1, and thresholds were fixed at the average of all experiments.

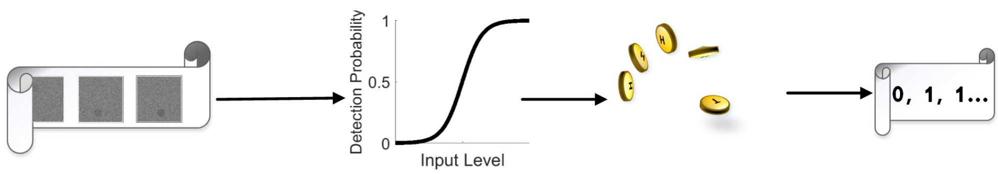


Figure 2.8: **Instantaneous Model** represents the input-output relations of sigmoid transference function that the defines the probability of a positive response. A stochastic element is determining the specific output for each input level, according to this probability.

Figure 2.9 shows the results for a set of these model observers, simulated for each of the three stimulus regimes, marked in red. As expected, while the White stimulus causes a chance-level of approximately 0.5 probability of alternation, the slower stimulus elicits less response alternation, even without any history-dependence on the observer's part. The same figure shows also the POA computed from the experimental data, marked in black, showing that experimental POA values are lower compared with those of the instantaneous model, for all stimulus regime. This reflects an inherent tendency of the observes to repeat the same response as the previous one, generating streaks longer than justified from the input. The effect is similar in magnitude (experimental POA approximately 0.08 lower than instantaneous model) across all three stimulus regimes.

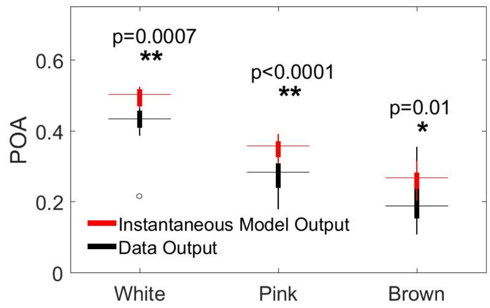


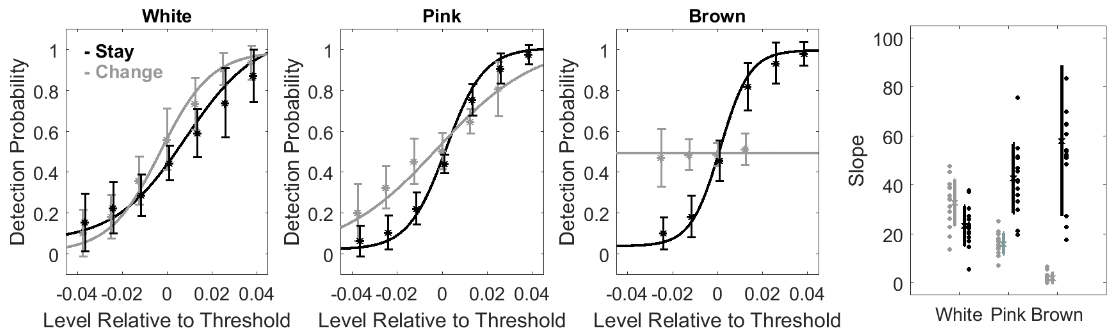
Figure 2.9: **Probability of alternations (POA)** computed for human subjects (Black) and for 15 instantaneous model subjects (Red). Means: horizontal lines, error-bars: 95% confidence intervals. Two sided T-test for the difference between the groups of values performed, significance is marked with asterisks, p-values are noted.

These results did not change if all instantaneous observers used the same psychometric function with the same slope, as can be seen in the Appendix, in A.1.2 figure A.2.

2.2.3 Different slopes in psychometric curves conditioned on response

The results presented above show that, on average, observers tend to switch their response less often than is required by the input stimulus. To characterize this property in more detail we compute the psychometric curves conditioning on the current and previous responses. We divide all trials to those where the response stayed the same and those where the response changed compared to the previous trial. Fig. 2.10 shows the separate psychometric curves conditioned on these two events, for the three stimulus regimes. Consider first the Brown stimulus: here trials that were the same as previous trials maintain a relatively sharp sigmoidal relation with the stimulus (black curve), while those that contained a switch in the response seem completely random, i.e. unrelated to the stimulus value (grey curve). Despite the low statistics of this conditional response curve (in the Brown stimulus there are few instances justifying a switch in response), still the effect is significant. It implies that without reference to the stimulus, the observer has a probability of switching his/her response, possibly following a long sequence of same responses required by the Brown stimulus.

The same effect appears, though not as strong, for the Pink stimulus: those trials for which the response switched were ”noisier” than those that did not switch, namely the psychometric curve slope was smaller. In the White stimulus, in contrast, we find an opposite (though small) effect: those trials with changed responses were more informative about the stimulus. This implies that, when the stimulus changes rapidly, the observer tends to switch responses *less* than required by the stimulus. Taken together, these results suggest that both positive and negative biases exist, relative to the instantaneous response dictated by the stimulus; these different biases are exposed in different stimulus regimes.



(a) Conditioned psychometric curevs (b) Subjects fit slopes

Figure 2.10: **Psychometric curves conditioned on response**
(a) Trials were divided to two groups: those where the response stayed the same (Black) and those where the response changed compared to the previous trial (grey). Conditional psychometric curves have different slopes; the magnitude and direction of the effect is different in the three stimulus regimes. In order to overcome some of the variability between subjects the individual curves were centered to each own threshold, and the binned levels are with respect to this center.
(b) Values of individual subjects slopes of stay / change psychometric curves (fitted to sigmoids).

2.2.4 Hysteresis in psychometric curves conditioned on input

We have seen that conditioning the psychometric curve on output temporal sequences reveals a bias with respect to consecutive responses. However, since responses are correlated with inputs, these biases can be caused by input temporal sequences rather than (or in addition to) output sequences. Therefore we analyzed also psychometric curved conditioned on properties of the input signal. Responses were divided into two groups depending on the nature of stimuli preceding the one which related to the current response.

Figure 2.11a shows the results for a white input signal, with the division into two groups determined by whether the current stimulus is larger or smaller than the previous one. The red curve, "Up data", corresponds to all trials in which the current stimulus was higher than the previous one. The black curve, "Down data", is constructed from trials in which the current stimulus was smaller. In this figure the two curves show positive hysteresis: the "up" curve has a higher threshold than the "down" curve. Such positive hysteresis indirectly reflects a tendency to repeat the previous response: for the same input level, coming from high stimulus our perception is higher than coming from a previously lower one. The difference between the thresholds of the two conditional curves is shown in the inset, for all three stimulus regimes. It is seen that the effect is strongest for White input and decreases to an insignificant value for the Brown input. This can be partially explained by the fact that, in a slowly-varying stimulus, changes between consecutive input levels tend to be very small, whereas in the white stimulus they can be of any magnitude.

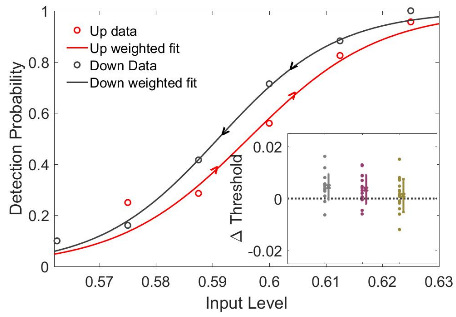
This analysis reveals a sensitivity to the change in stimulus, but takes into account only the current and previous trials. It restates, from a different angle, the tendency of observers to "stick" to their previous response with higher probability than dictated by the stimulus.

A generalization which takes into account longer history, is achieved by comparing the current stimulus to the past history over a timescale τ. Then, trials can be divided into two groups depending on whether the current input value is higher or lower relative to the general trend in the past history of length τ. Specifically, the input levels are filtered using an exponential filter of time constant τ; the result compared to the current input level. (Technical information regarding the process is elaborated in 2.1.2.3)

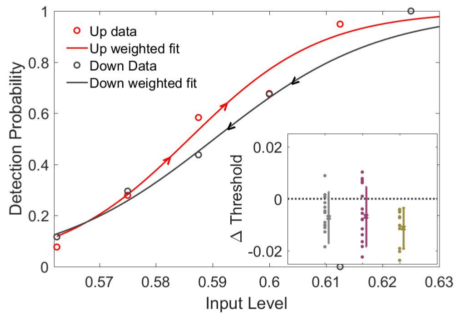
Psychometric curves and sigmoid fits were computed independently for the two groups, Up and Down, as before. An example is shown in figure 2.11b, where a timescale of $\tau = 32$ was used for defining the past input trend. For such a high τ value, the division into two groups reflects the current input relative to a general trend of the recent past rather than an immediate change of input level.

In contrast to the previous plot, here we find a negative hysteresis effect, namely the threshold for Up trials is lower than for Down trials. A similar effect was found for all stimulus regimes. Negative hysteresis reflects an increased sensitivity moving from a weak to a stronger stimulus, which is usually referred as adaptation. Such adaptation is typical to slowly changing environments that allow reliable prediction, where each change from the prediction results in an enlarged reaction. Indeed, this effect was prominent in Brown session where input levels were actually changing slowly.

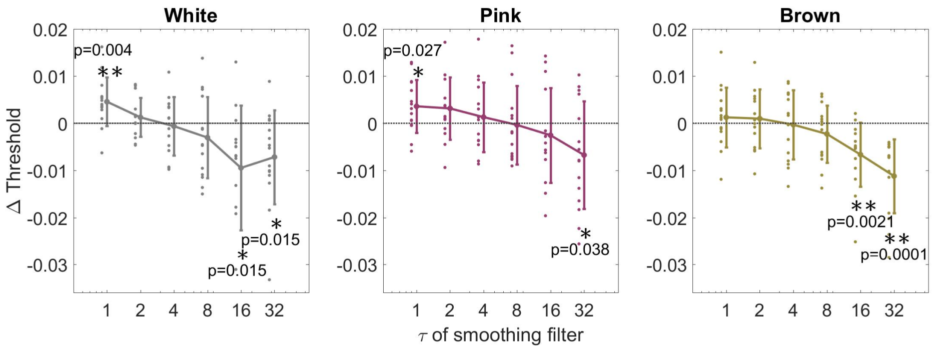
Quantifying the degree of hysteresis as the difference between thresholds of "up" and "down" curves, allows us to plot this difference for a range of τ values, corresponding to the length of history defining the trend. For the special case of $\tau = 1$, the signal was not filtered at all so "up" and "down" simply refer to the difference between current and previous signals. Figure. 2.11c shows the result of this analysis, depicting all individual observers as dots as well as averages and standard deviations as errorbars. The trends are clear and similar for all stimulus regimes: in the short term a positive hysteresis appears, which decreases with τ until it eventually crosses over to a negative hysteresis over long times. The White stimulus reveals the largest magnitude of positive hysteresis, whereas for the Brown stimulus the negative hysteresis dominates. These results show that both processes, positive and negative biases, exist in human observers. It appears that they emerge with different characteristic timescale - positive bias over short times and negative bias over longer times. The ultimate response pattern results from an interplay of the two, and depend on the temporal nature of the stimulus.



(a) Positive hysteresis with $\tau = 1$



(b) Negative hysteresis with $\tau = 32$



(c) Hysteresis with various τ values

Figure 2.11: **Positive and negative hysteresis in conditional psychometric curves** (a) Example of "Up" (red) and "Down" (black) psychometric curves, conditional on whether the current stimulus is higher or lower than the previous one. Stimulus was White in this experiment. Data points: circles, sigmoid fits: lines.
Inset: magnitude of hysteresis *in all stimulus regimes*, defined as the difference between thresholds of "Up" and "Down", for all subjects: $Hystersis(\tau) = Th.(\tau)_{up} - Th.(\tau)_{down}$
(b) The same as in (a) only with conditioning on "Up" and "Down" of the current stimulus relative to a trend over $\tau = 32$ previous trials. Hysteresis is negative here: "Up" has lower threshold than "Down".
Inset: Hysteresis values of all subjects in the *all stimulus regimes* with $\tau = 32$.
Examples (a)&(b) are taken from subject IR_F_23.
(c) Hysteresis of all subjects in all stimulus regimes, at various lengths of exponential filters defining the past trend (τ).
T-test performed against null hypothesis, significant values are marked with asterisks and p-values are noted.

2.3 Model

The experiments presented above suggest that, in addition to the input signal, two inherent opposing forces act to shape perception. On one hand, human observers tend to stick to their previous responses even when stimuli change. On the other hand, over longer timescales, an adaptation effect occurs which effectively pushes the observer away from a constant response for too long. Below we construct several models for perception and examine their consistency with the results across all stimulus regimes. All models are based on an instantaneous input-output function (sigmoid) with two history-dependent modifications representing the two forces described above. The basic instantaneous model is the same sigmoidal model which used for comparison of POA levels between the regimes, see figure 2.8.

The basic structure of the models is composed of two stages: a *sensory* part, in which the input signal passes through a static nonlinear (sigmoid) response function that defines a probability of detection and a *cognitive* process, in which the final decision is made on the response.

Upon this basis the history-dependent modifications can be added. Adaptation in this process can be implemented by a modification of the the sigmoid threshold, or equivalently, by adding a bias to the perceived signal [5]. Therefore, adaptation is applied in the sensory stage; The input signal is *linearly* filtered before it passes through the nonlinear (sigmoid) function, this is known in the signal processing context as a "linear-nonlinear" model [43].

It is now followed by a *cognitive* process, in which the final decision is made on the response. A coin flip according this probability is determining the final response. At this point additional factors such as previous response, current state of attention may alter the probability, hence influence the decision.

2.3.1 Sensory-Cognitive model - dependent on history of inputs and responses

The general structure is depicted as a black backbone in Fig. 2.12, with the history-dependent modifications drawn on top of this backbone by red arrows. Here adaptation acts on directly on the input whereas the cognitive process is affected only by the output. This partition of the two history-dependent modifications is consistent with recent fMRI experiments [54], indicating that they are mapped to distinct brain regions. Specifically, adaptation was related to primary visual areas whereas positive recency was related to high cognitive areas, whereas the second to primary areas of the visual system.

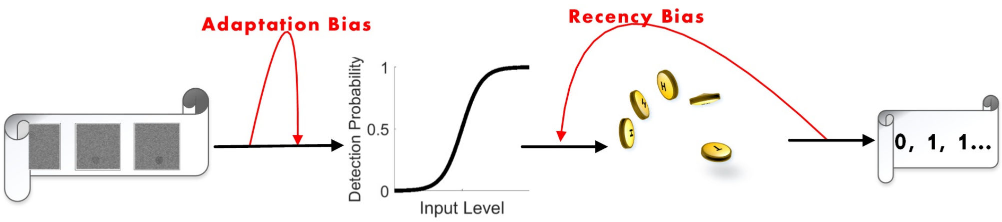
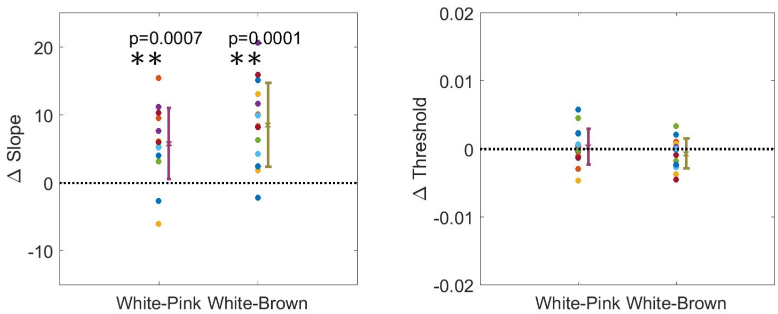


Figure 2.12: **Sensory-Cognitive model.** The backbone structure of the model (black arrows) is composed of a fixed input-output relation (*sensory process*) and a probabilistic "coin flip" decision based on the resulting output *cognitive process*. Upon this process 2 biased are added (red arrows): an *Adaptation Bias* varies the threshold based on the input history; and a *Recency Bias* can modify the final decision based on previous responses.

We used this model to generate a set of 15 observers, and simulated the same protocol as the experiment. Sets of input signals were synthesized in the three stimulus regimes, presented to the model observers, their responses (0/1) recorded, and the results analyzed using the same analysis as that used in the experiments. The results are presented in Figs. 2.13-2.16.



(a) Slope of Model subjects

(b) Threshold of Model subjects

Figure 2.13: **Empirical psychometric curve parameters in the model.** Results of 15 model-observers were analyzed for their empirical psychometric curve under the three stimulus regimes. Relative slopes (2.13a) and thresholds (2.13b) were computed by subtracting the parameters of the Pink and Brown experiments from those of the White, for each individual observer, similar to the analysis of the human subjects. Compare to experimental results in Fig. 2.7.

First we used the responses of the model observers to construct their empirical psychometric curves. Although the input-output sigmoid function defined in the model (middle box in Fig. 2.12) was fixed, the existence of history-dependence in the model together with different temporal structure of the inputs resulted in empirical psychometric curves that depended on the stimulus regime. Fig. 2.13 depicts the difference between parameters of these empirical curves for the two correlated inputs - Pink and Brown - and those computed for the White stimulus. Similarly to the human observers, the model produced sharper psychometric curves (larger slopes) for the slowly varying simuli (2.13a), while the threshold values remain unchanged (2.13b). The effects are similar in direction and in magnitude to that found for human observers.

Next we considered the probability of response alternation (POA) averaged over the entire experiment, for the different stimulus regimes. Fig. 2.14 shows the results for all model observers (red) together with the same quantities computed for the experiments on human observers (black). They are practically indistinguishable, showing that the model captures correctly the tendency for positive recency equally well in all stimulus regimes.

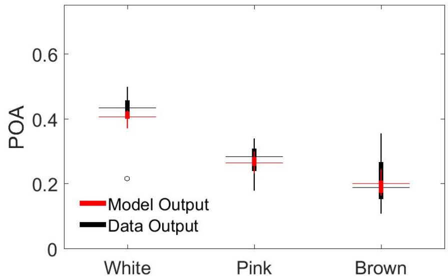


Figure 2.14: **POA of model and data** Probability of alternation in response (POA) of humans subjects (Black) and of model subjects (Red).

The model also captured the empirical psychometric curves conditioned on the response, as well as those conditioned on the stimulus trends. Fig. 2.15 shows the results for conditioning on whether the response was repeated or changed relative to the previous one, which can be compared to the experiment in Fig. 2.10. Fig. 2.16 shows the hysteresis - difference in thresholds between the two conditioned groups - for conditioning on the direction of stimulus changed, defined over various timescales. This can be compared to Fig. 2.11: the model shows the same hysteresis profile as a function of the timescale used to define the trend in the stimulus. Note that, since the 15 observers had the same model parameters, variability between them is smaller than between human observers, as expected.

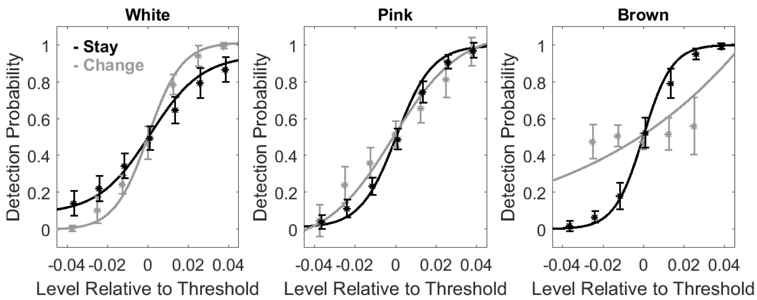


Figure 2.15: **Model psychometric curves conditioned on response** Trials were divided into those in which the response was the same as in the previous trial ("stay"; black) and those in which it changed ("change"; gray). Compare the results with experimental data in figure 2.10.

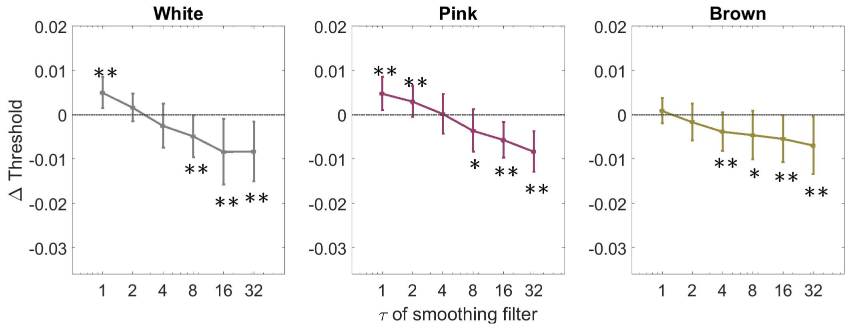


Figure 2.16: **Hysteresis in model psychometric curves conditioned on stimulus trend** Hysteresis in model shows qualitatively the same behavior as a function of τ, the timescale used to define the stimulus trend as Up or Down, as human observers, for all stimulus regimes. Compare the results with experimental data in figure 2.11.

2.3.2 Sensory-Cognitive model - dependent only on history of responses

Other models that differ in details of the history-dependent effects were also tested. For example, the dependence of the adaptation bias (threshold modification of the input-output curve based on a history of length τ) could be made to depend on the output rather than the input. A sketch of this model is presented in Fig. 2.17. The results of model observers following these processes were indistinguishable from the one presented above. Other possible combinations were also tested, but were found to be more sensitive to the choice of parameters than the two model versions mentioned here.

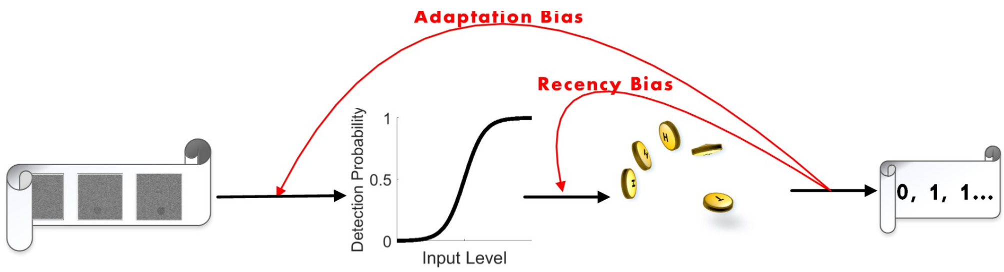


Figure 2.17: **Sensory-Cognitive model - dependent only on history of responses** The regulation of the adaptation bias of the input is based upon the responses history, rather than on the input history.

Chapter 3

Audio-Visual experiment - relations between the modalities

3.1 Methods

3.1.1 Experiment Procedure

3.1.1.1 General

Combined Audio-Visual experiments were conducted to evaluate the dynamical influence of one perception on the other. The experiments investigated relations between detection performance in two modalities, under different contextual relations with the perceived object.

Each subject sat in front of a computer screen in a dark room wearing headphones. Consecutive combined trials were applied, each trial included background stimuli in both modalites concomitantly, but only in one (random) modality a stimulus was actually delivered upon the background. Subjects were asked to respond with a key press: pressing '1' for noticing either stimulus, or '0' when neither auditory nor visual stimulus was noticed. Response was identical with respect to seeing or hearing, subjects were not required to classify the type of stimulus.

24 subjects (13 females) participated in the experiment, aged 21-32. All of them had regular or corrected to regular vision, regular hearing and were not diagnosed as having attention deficit disorders and were naive to the purpose of the experiment. Subjects signed a consent form and were paid for their time. 3 subjects (3 females) were excluded from results for having 15% or more false positive responses to sham trials. 2 more (1 female) where also excluded because of an extreme difference in performance between the different sessions (details in 3.2.1).

3.1.1.2 Visual stimulus

The visual stimulus was the same as in the visual experiment which is described in details in section 2.1.1.2 and is shown in figure 2.1.

3.1.1.3 Auditory stimulus

The auditory stimulus was a beep embedded in noise. The background was white noise, bandpass filtered to the range between 800-1200Hz, with a duration of 2 seconds. The beep was 1000Hz pure tone of 0.2 seconds long. See example in figure 3.1. The delay of the beep from the beginning of the background noise was randomly selected in every trial out of three options: 0.75, 1 or 1.25 seconds. Background noise level was kept constant throughout the experiment, thus while beep levels were changed between trials. From here on the term “auditory level” refers to the ratio between the beep energy and the total energy (beep+noise) in the same period of time.

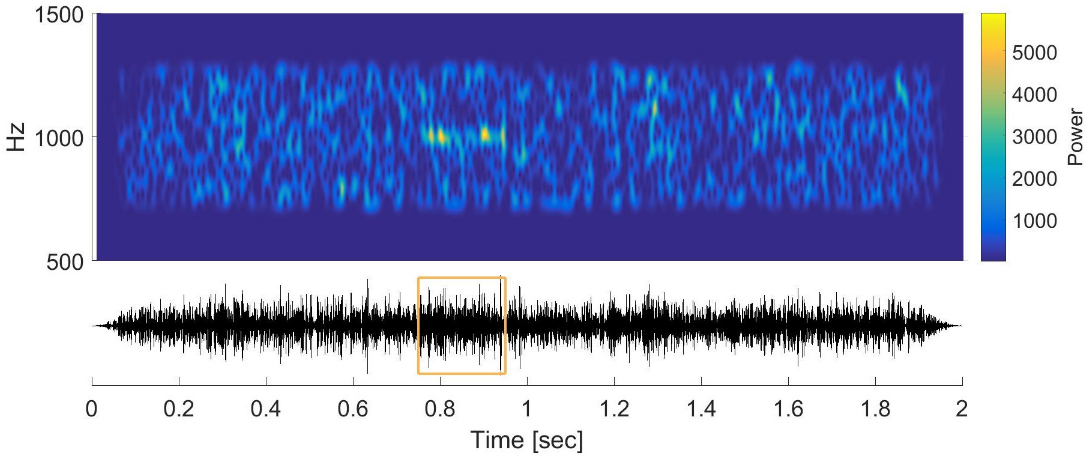


Figure 3.1: **Auditory stimulus** Background noise lasts 2 seconds and the beep, which embedded in it, is 0.2 seconds long. In this example beep starts 0.75 seconds after the beginning of the noise.
The upper panel shows a frequency-temporal decomposition of one trial. Background noise is ranging from 800Hz to 1200Hz and beep is played at exactly 1000Hz.
The lower panel shows the total energy of the signal. In this example the auditory level is 0.2 (see previous paragraph for definition of auditory level). Although it is hard to notice in the signal in the trace (marked with an orange rectangle) this level makes a very clear ’beep’ when it is heard. .

3.1.1.4 Audio-Visual combined trial structure

Each trial was composed of 3 stages. A timeline which is presenting one audio-visual trial is shown in figure 3.2.

- **A reset period** of 0.75 seconds contains the auditory background and a blank rectangle with a central fixation circle for the visual reset.
- **A stimulus period** of 0.75 seconds is when concomitant visual & auditory backgrounds are presented: noise and a visual black & white dotted image, respectively. Only in one modality, either the auditory or the visual, a stimulus is presented on top of the background during this period .

- **A response period** is the final stage where an auditory background noise continues for 0.5 seconds (to a total of 2 seconds) and is followed by silence. While the visual reset screen is displayed. This state continues for an unlimited duration while the system is waiting for the subject to respond.

Once the subject responds, the next trial begins.

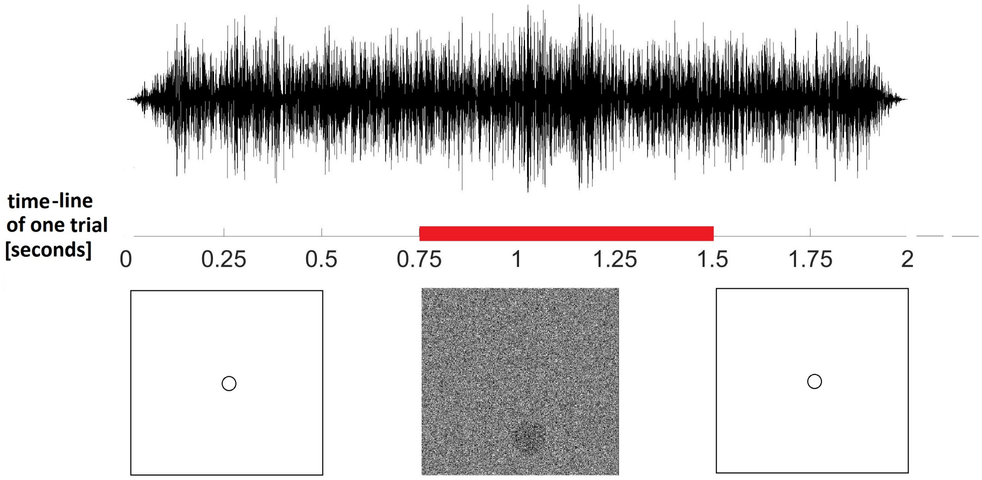


Figure 3.2: **Audio-Visual trial** The trial begins with a background noise and a background white image. The stimulus period, in which the visual background (with/without spot) is shown, is noted with a red line on the timeline. This is also the range of time in which the auditory beep may begin. In this example beep starts 1 second after the beginning of the trial.
For demonstration both beep and spot are shown on top on the background, while in the actual experiment just either of them is presented in any trial.

3.1.1.5 Experiment structure and closed loop procedure

The experiment consisted of 4 sessions of 300 consecutive combined trials. In every trial the modlaity of the stimulus was randomly chosen. Sham trials, in which no stimulus was presented in any modality were randomly admixed. Some subjects (n=7) has 30 sham trials and the others (n=17) had 10 sham trials per session. In every session, each modality was presented with 135-145 stimuli.

The difference between sessions was the type of the relations between the input levels (of either modality) to the subject responses. For each subject the first session was a session where both modalities had **closed-loop** (CL) relations between inputs and the responses. The closed-loop procedure wss adapted from the principle to voltage clamp, and was demonstrated in visual psychophysical setting in the work by Marom & Wallach in 2011 [38].

Closed loop relations means that inputs are adjusted according to the previous responses. For each modality separately, a controller tracked responses of relevant stimuli and by filtering them created a measure of the *momentary detection probability*.

When the detection probability was higher than 0.5 (the "clamp level") it effected the following stimulus level to be lower than the previous one, which resulted with a harder stimluli for the subject to detect (lower contrast, or lower power of beep), It was vice-verse when detection probability declined below this level. Detailed description of the controller, its parameters and the momentary detection probability calculation are found in Methods 3.1, equations 3.1 to 3.3.

The first session was marked VCL_ACL (Visual CL - Auditory CL) i.e. each modality had an independent close-loop controller which determined the level of its input stimuli.

A different type of session was an open loop session, where no relations between the subject responses and the input levels existed. Instead, the input levels were **Replayed** (RE) in the same order as they were in the first session, such that statistics of inputs and the temporal structure were almost identical to those of the first session. The only difference was that there were new random admixture of sham trials amongst the trials. This session was marked VRE_ARE (Visual Replay - Auditory Replay). The other 2 sessions were mixed such that one modality's inputs were controlled in closed-loop and the inputs of the other were replayed (open loop) from the first VCL_ACL session These mixed sessions were marked VCL_ARE and VRE_ACL.

For every subjects the first session was always VCL_ACL and the order of 3 other sessions were randomly shuffled between subjects. VCL_ACL session was 25 trials longer, the first 25 trials were used only for stabilizing the controllers and were not replayed in following sessions, nor they were included in analysis.

3.1.2 Technical Details

3.1.2.1 Closed Loop: PID controller

Closing a loop on response is effectively a process of on-going adjustment of stimuli levels according to the momentary detection probability (DP). The purpose of this adjustment is to flatten response fluctuautions, such that the DP (detection probability) stays as close as possible to a desired value, the clamped level (in our experiments 0.5 DP).
For the estimation of DP we apply a smoothing exponential filter on past responses. There is a separate controller for each of the modlaities which is updating only according to responses to stimuli of the same modality.

DP estimation is performed by applying an exponential filter on responses. It is given by the formula:

$$DP_n = (1 - e^{-\frac{1}{\tau}}) * Response_n + (e^{-\frac{1}{\tau}}) * DP_{n-1} \tag{3.1}$$

The error to be minimized is the distance of the DP from 0.5:

$$err_n = 0.5 - DP_{n-1} \tag{3.2}$$

Note that err_n can be either positive or negative, with respect to the size of detection probability. Next input level is determained by a Proportional-Integral-Differential controller (PID), implemented in this way:

$$x_{n+1} = x_0 + (err_n) * P + (\sum_{i=1}^{n} err_i) * I + (err_n - err_{n-1}) * D \qquad (3.3)$$

Specifically for this experiment we used the following constants: $P = 0.2, \quad I = 0.02, \quad D = 0.002, \quad x_0V = 0.7, \quad x_0A = 0.2$
Note that visual level and auditory level refer to different qualities, accordingly each of them has an individual initial level: x_0V for visual and lx_0A for the auditory stimuli.

3.1.2.2 Detection probability calculation

The calculation of ongoing DP was performed separately for each modality. Responses were devided by the modality of the stimulus while the original time of responses were kept to maintain time synchronization of the two modaliteis traces. Whe DP was estimated in post processing we used the same filter which was used in the closed loop session (equation 3.1). In order to avoid the transient period of controller stabilization the first 25 responses of all sessions were precluded from further analysis in all sessions (in addition to the first 25 trials in VCL_ACL session that were not replayed).

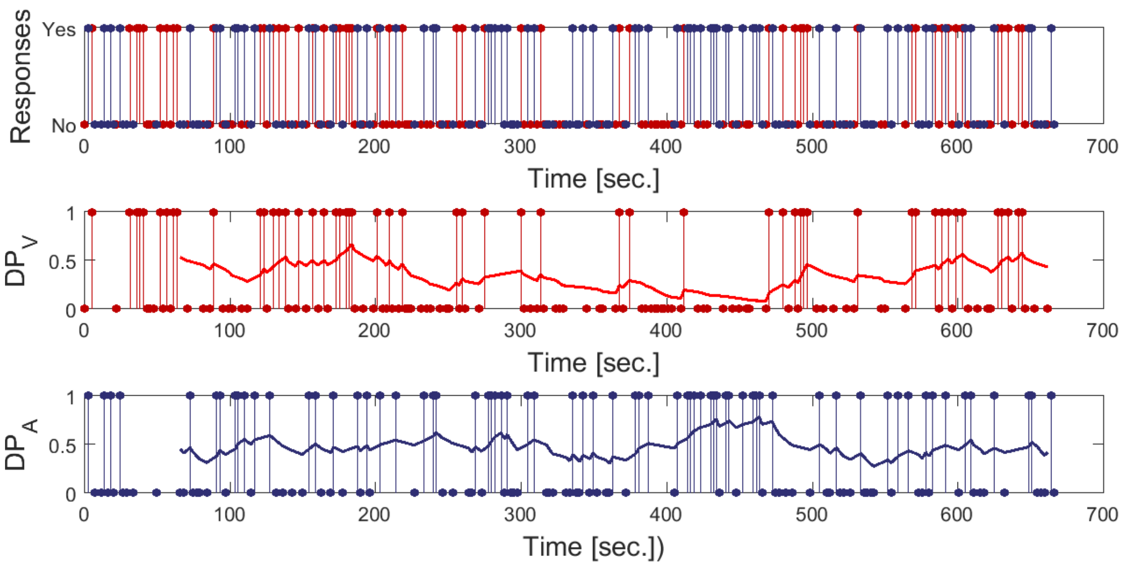


Figure 3.3: **DP Calculation Example** Top panel: all responses, red circles for visual and blue circles for auditory stimuli. In the 2 lower panels the responses are separated by the modality of the stimulus . Solid bold lines show the filtered values, which represents the momentary detection probability of each modality (upper, Red for visual , lower, Blue for auditory).

3.2 Results

The current experiment was examined in 4 ways: Initially, we compared the global measures of performance amongst sessions. Second, for each modlaity, we tested the how the regime of the counter effects the fluctuations of the first. Third we investigated the temporal relationship between the modalitied. And last, we investigated whether a recency effect occurs within and/or between the modlaiites.

3.2.1 Total rate of detection in closed and open loop does not change

In order to establish foundations for the comparison between the experiment modes we compared the over all performance between them. We found that on average the total rate of detection did not alter whenever subjects performed the task in open or closed loop, as seen in figure 3.4.

It is expected that in closed loop all subjects had around 0.5 detection rate, since the closed loop controller is ensuring that. In open loop, for the specific subjects it occurred that the total rate in open loop was higher or lower than 0.5. But on average across all subjects the positive responses were also around 0.5.

Two subjects were excludes from the rest of the analysis since they had an overall detection rate (in at least one open loop session) which deviate extremely from 0.5. Specifically, the deviation was more than 2σ from the mean detection rate of all subjects.

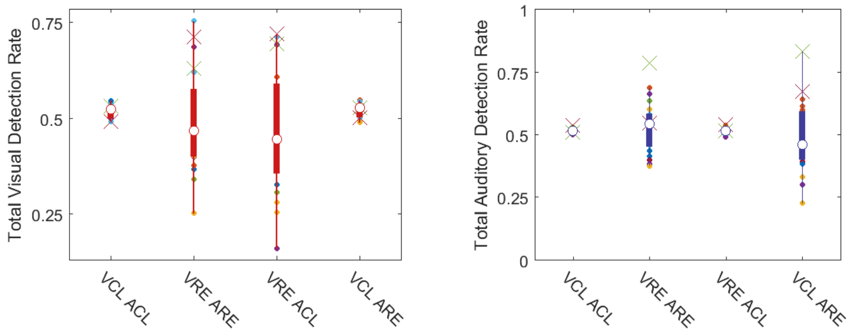


Figure 3.4: **Total detection rate** is on average the same in all the 4 sessions. On the left, in red, the total portion of positive responses of visual stimuli. Performance of individual subjects are marked with a dots. Red area stands for the STD around the mean of the subjects, thin lines represents confidence level of 95%, and the white circle is the median. On the right, in blue, same marking for auditory responses. 2 subjects which had extreme results are marked with an 'x'.

3.2.2 Response fluctuations in closed / open loop - the influence of counter modality

In order to estimate fluctuations in response we inspected the temporal detection, rather than over all performance. We estimated the momentary detection probability (DP) for each modality as described in the technical details section 3.1.2.2. Figure 3.5 shows an example of one subjects response fluctuations in all 4 sessions.

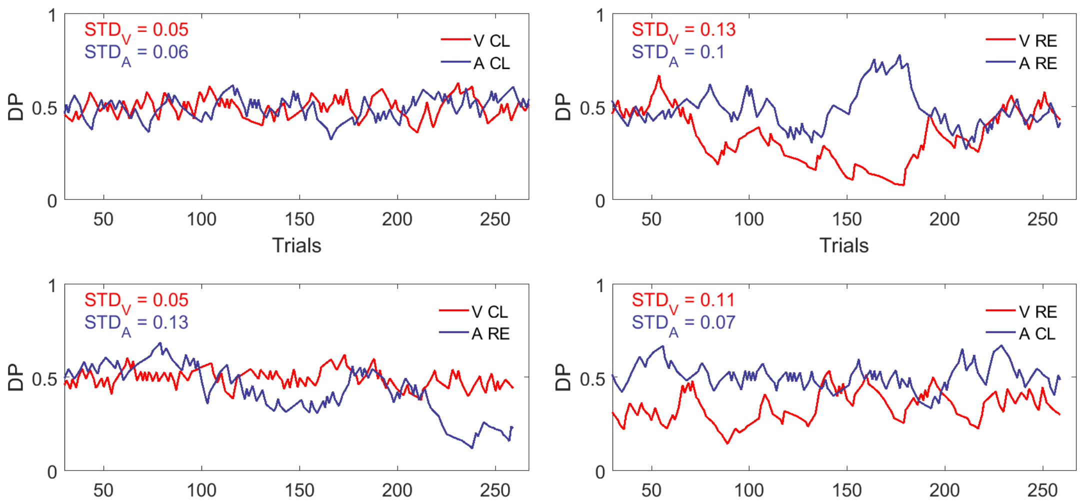
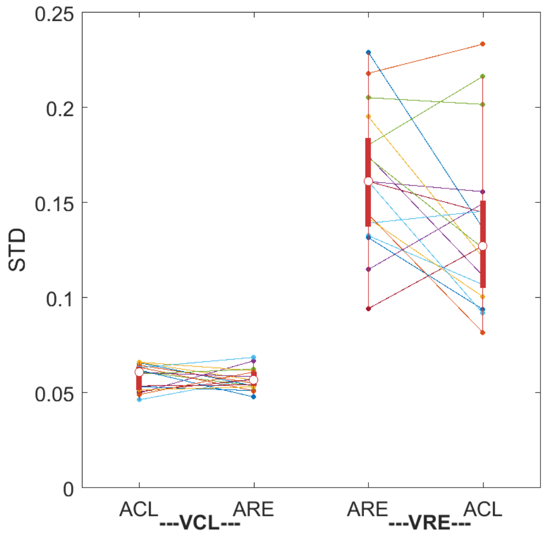


Figure 3.5: **Example of response fluctuations in all sessions** the 4 panels show filtered responses of all sessions of one subject. Red are responses for visual stimuli and blue for auditory stimuli. Fluctuation levels are expressed as the standard deviation of the filtered response.

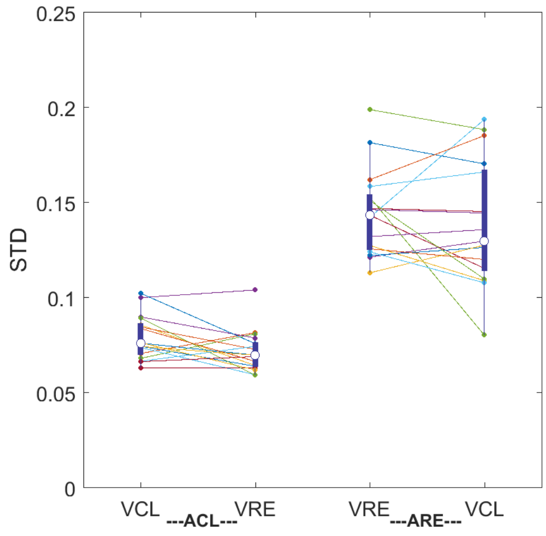
It was expected, and indeed found, that a modality which was in closed loop displayed less fluctuation than when it was in an open loop, since the closed loop was "clamping it" to do exactly so.

Figure 3.6 summarizes the fluctuation levels of all subjects. For the inspection of the interactions *between* the modalities we checked the influence of the second modality being in open/closed loop on the fluctuations of the first when itself was in *open loop*. The results show that influence indeed exists, but only in one direction; When auditory was in open loop the the visual fluctuations decreased, relative to the case where both modalities were in open loop, as seen on 3.6a. however, such influence was not found in auditory open loop where fluctuations have not changed whenever the visual modality was either regime, see 3.6b. The meaning is that we found an asymmetry between the modalities: only the fluctuations of the visual response were effected by auditory relations with response (closed or open loop) while auditory was not influenced by visual relations with response.

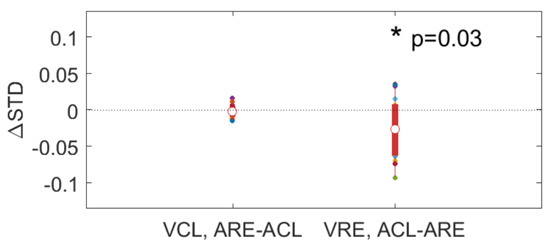
When either modality was in closed loop, the effect of the controller of suppressing the fluctuation was dominant, no interaction was found between the modalities.



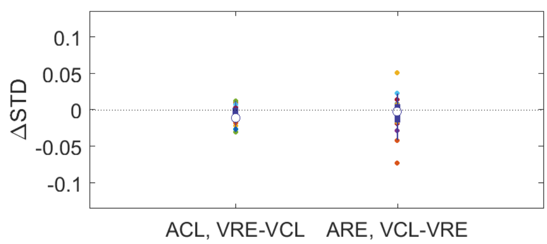
(a) Visual



(b) Auditory



(c) Visual - influence of auditory CL/RE



(d) Auditory - influence of visual CL/RE

Figure 3.6: **Fluctuations of response** in the different experimental conditions:
(a)&(b): Pairs of STD levels of the DP traces of visual (Red) and auditory (Blue) responses in the different experiment conditions. Dots represents individual subjects,the lines which connect every pair of dots show the individual trends. Error-bars mark the standard deviation (1σ) around the mean fluctuation levels of all subjects, median is marked with a white circle.
On the left of both panels - STD levels of either modality when itself is in CL are low, and are not effected by the regime of the other modality. (a) On the right - visual DP fluctuations are decreased when auditory alone was in a CL relative to the session when both modalities were in OL. (b) On the right - Auditory fluctuations in OL do not change whenever visual modality is in either regime.
(c)&(d): Since fluctuation levels are highly diverse between subjects we are looking at the individual difference (ΔSTD). On average, in open loop sessions $\Delta STDs$ of the visula responses are lower than zero. This reflects a per-subject influence of auditory fluctuations on the visual fluctuations. Statistical significance with respect to the null hypothesis was found using t-test, p-value was 0.03.

3.2.3 Temporal relationship between responses to Auditory and of Visual stimuli

Another way of inspecting the temporal relations between modalities was directly looking at the dynamic relations between their two response traces. The traces of the two modalities were calculated while aligned to their actual times. The filetred repsonses were then extrapolated to be evaluated also at times of stimulation of the other modalitiy. These aligned and extrapolated traces enabled to calculate a temporal cross-correlation between them. Same process, extrapolations and cross-correlation, was applied also on the two vectors of input levels.
We calculated a normalized cross-correlation for each pair of signals by the formula:

$$Xcorr(A,B) = \frac{1}{N-1}\sum_{i=1}^{N}(\frac{A_i - \sigma_A}{\mu_A})(\frac{B_i - \sigma_B}{\mu_B}) \quad (3.4)$$

Where N is the signal length and σ and mu are the mean and standard deviation of the signals, respectively. This revealed complex temporal relations between the modalities as seen in figure 3.7.

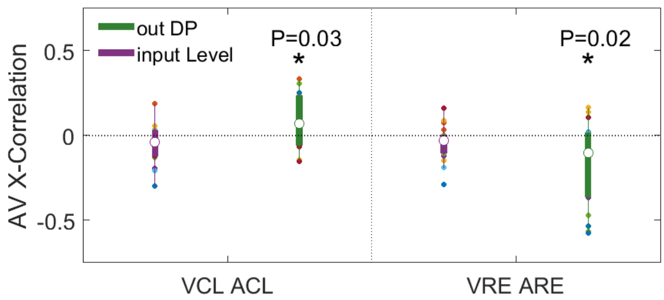


Figure 3.7: **Auditory-Visual X-correlation of Inputs and DP**
The output responses have a *positive* correlation between them when both modalitied in closed loop (green on the left), while a *negative* correlation is found when both of them in the replay (open loop) session (green on the right). There is zero correlation between input levels in both cases (purple, both sides)
Statistical significance was calculated using t-test for X-correlation levels against the null hypothesis; asterisks mark significance and p-values are noted.

Any audio-visual correlation (both directions) cannot be accounted to any property of the input itself because the auditory and the visual inputs have zero correlation between them. Moreover, the difference between the correlation direction in open loop and closed loop occurred in spite of the (almost) identical inputs which were delivered in these two sessions.

A *Negative* correlation was found between the responses of the modalities when they were both in open loop session.(A representative example of the counter correlations in open loop is shown between the traces of the subject in figure 3.5, top on the right).

This can be accounted for temporal and voluntary **shifts of attention** between the modalites. Closed loop paradigm prevented these shifts, as we showed that the correlation between responses in open loop was *Positive* for the same inputs (an example for the small positive correlations between DP traces in closed loop is shown in figure 3.5, top on the left).

Although each modality had an independent controller the process of relating to the response itself entrained fluctuations of the two modalities to each other, so they became correlated. The way it may occurred could be for instance, if the subject was focused during some period of time on the visual stimuli while "neglecting" the attention to the auditory ones, than the controller would have strengthened the next auditory stimuli to the extent it became inevitable not to detect. The result, in this case, was concomitant alertness to both sources of stimuli.

3.2.4 Audion and vision responses in the combined experiment have no recency effects

A known tendency in perception is the 'recency effect', which means that subjects tend to repeat last response more than justified by the input structure (the effect was demonstrated in the visual detection process in section 2.2.2). Hereby this effect is evaluated in the bi-modal case;

In the current experiment the stream of results was mixed, i.e. composed of responses to auditory and visual stimuli. There were two ways to inspect the recency effect such a case, asking:

1. Is there recnecy whithin results of each independent modality although in half the cases stimuli were not actually consecutive?

2. Does this effect exists for the general responses of combined inputs sources?

The measure that we used for evaluation of the effect is Probability Of Alternation (POA), which is defined in equation 2.11 in chapter 2.2.2.

3.2.4.1 No recency effect within each modality

In order to test the first question responses were separated into two vectors, auditory responses and visual responses and POA of each of them was calculated separately. The inputs of each modlaity were generated by the closed loop controller which resulted in an individual temporally-correlated input levels for each modality. Since a structure of the input dictates the level of reference for probability of alternations (i.e. the POA which is expected without recency and other biases), therefore, we had to consider the actual structures that were delivered.

We used an instantaneous model to evaluate this expected value as follows: The model reflected the static & memory-less properties of the input-output relations for either modality (elaborated description of this model is found in the previous chapter 2.2.2 and in figure in 2.8). The parameters that were used in the model were the average values (across all subjects) of slope and threshold for either modlaity. These values were obtained for each subject by generating psychometric curves for both auditory and visual responses, and than extracting the slope and threshold of each curve by fitting it to a sigmoid as described in 2.1.2.1). To be most precise, the inputs that were fed to the model were the actual inputs which were presented to the subjects in the open loop session (a "replay" of the ones recorded in the closed loop procedure).

In the case of closed loop it was expected to find high alternation rates since, each controller prevented long streaks *in its modality.* Indeed, in figure 3.8 these high alternations rates stick out wherever either modality is in closed loop, regardless the regime of operation of the other modlaity. However, in open loop, we found that responses to each modality *did not have tendency to recency.* For example, the visual series of responses to open loop stimuli were the same as the instantaneous model, under auditory open loop (left panel, VRE_ARE) and under auditory closed loop (left panel, VRE_ACL). In comparison to the results of the experiment in visual modality alone 2.2.2, this implies that analyzing the visual trials alone in a series of mixed visual-auditory trials, the recency effect disappeared regardless of the manipulation applied on the other modality.

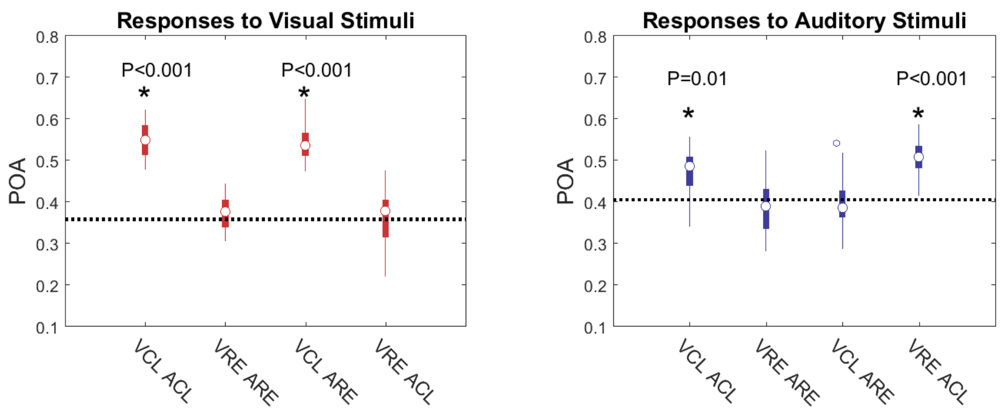


Figure 3.8: **Probability of alternation in responses per modality** On the left, POA of Visual responses. Red area represents STD between subjects around the mean, thin lines stands for 95% confidence level and white circle for the median. POA obtained from an instantaneous model applied to the input stimulus is marked by a horizontal dotted line. On the right, in Blue, POA of auditory responses. Asterisks mark significance for POA being different than the value dictated by the input structure (P-value for t-test is notated).

This finding, that no recency effect existed within each modality, could have been a result of the interrupts of the other modality in the sequence of responses, which dismissed the effect for the overall signal. To test this hypothesis, we checked if some recency existed specifically for the trails were the modality of the previous stimulus was the same as of the current one (on average these are half of all the trials of each modality).

The alternation rate of only consecutive trials of the same modality was calculated and surprisingly, in this case too the result did not change - within either modality there was no recency effect at all, see figure 3.9. This result is opposite to that one which we have found in the experiment of *visual modality alone*; There we have shown that recncey of responses exists beyond the inputs demand for all input structures. The difference in results highlights once again how specific context and experiment conditions, such as raising the cognitive load by admixing modalities, can alter results and even modify basic properties of detection.

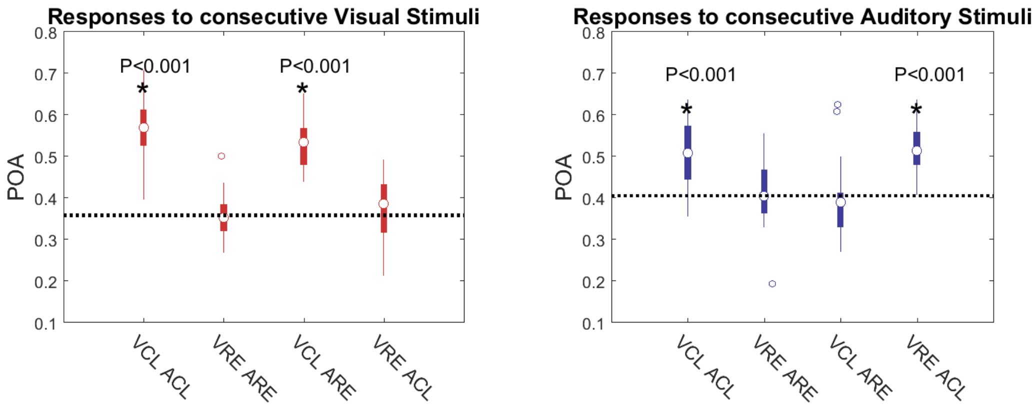


Figure 3.9: **Probability of response alternation per modality for consecutive trials of the same modality**
These cases are on average half of all the trails of each modlaity (67-72 trials per subject per session, dependent on the number of sham trials in the experiment).
Marking as in figure 3.8.

3.2.4.2 No recency effect between the modalities

For inspection of the second question - recency in the combined response, there was no need to separate the results vector, so POA of responses was calculated for it as a whole. For calculating the reference POA which is derived from the input structure we merged the instantaneous model outputs, generated for the previous analysis in 3.2.4.1, thus while keeping the original order of presentation. The response alternation rate was calculated upon this combined output, and comapred to the reference value. In figure 3.10 we see that also between the modlities there was no recency of responses beyond what is dictated by the input structure.

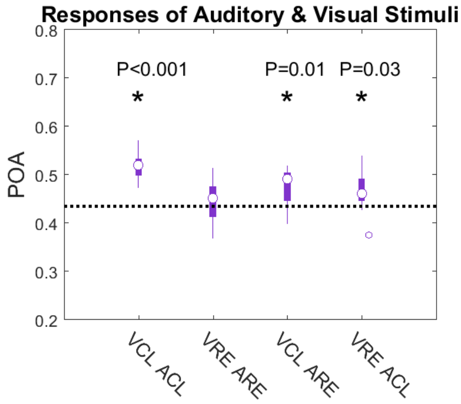


Figure 3.10: **Probability of alternation of all responses** The POA overall stream of responses in open loop is not lower than the alternation rate which is expected from input structure (marked with an horizontal line). There is no recency effect of inter-modality responses.

Altogether, we found that recency effect was not found in any way in this combined auditory-visual paradigm.

Chapter 4

Discussion

This thesis summarizes two sets of investigations studying two aspects of the dynamics of response fluctuations: temporal context effects and cross-modal interactions. The discussion is divided into two parts: the first is a review of the main results with elaborations on their interpretation and significance with some reservations; while the second part includes some points of criticism regarding both methodology and conclusions.

4.1 Comments on main results and few reservations

Perception seems adequate to natural conditions The first result of this study is that the steepness of the psychometric curve varies as the order of inputs presentation is changed. Specifically, the psychometric curve gets steeper as the inputs have more inner temporal correlations, while there is no influence of these correlations on the total detection rate. This reflects a reduced ambiguity for structured inputs. If we allow perception to be regarded as “good” and “reliable” when ambiguity is reduced, it implies that the more correlated (closer to natural) the experience, the more reliable its perception would be. In an additional analysis we showed at the same time that such stability of environment enhanced the sensitivity to change: when there was a slight change from the prediction there was an enlarged reaction. These results may be related to real world experiences which typically change slowly, while still sudden changes may indicate dangerous surprises which must be taken into account. Altogether, our results suggest that perception performance is adequate to natural conditions.

If viewed from an evolutionary perspective, and this is a consequence of an developmental process, this conclusion is not surprising.

The other side of the coin is that it could imply that synthetic, jumpy, unnatural experiences make perception less reliable and more vulnerable to distortion.

Realization of exploitation and exploration balance in perception Next we showed that a balance exists between two opposing tendencies: a recency effect and a contradicting tendency. The recency effect can be seen as an expectancy to *exploit* a certain consistency within the environment, which doesn't disappear even when the reality does not support its existence. The contradicting force reflects the tendency to resist a general trend of responses. Effectively this is an adaptation to contexts which is realized as enhanced sensitivity, as mentioned in the previous paragraph. It denotes that a prediction of the expected input will reinforce *exploitation* behavior. Therefore, there are two counter-balancing forces exerted on perception, with the two directions being exploitation and exploration forces. The trade-off between exploitation and exploration was studied comprehensively in fields of high-level cognitive behavior and decision making [12, 63]. There are also reports regarding neuronal mechanisms that may underlie these behaviors [17]. It has been suggested that a similar mechanism exists on the perceptual level (review [4]). Our findings confirm that a similar trade-off mechanism between exploitation and exploration does indeed exist in perception, and we demonstrate how such a balance is realized specifically in perceptual detection tasks.

Time-scale saperation between the contradicting effects affects their dominance for different inputs In addition to confirming the existence of such a trade-off mechanism, we also found a timescale separation between the two opposing tendencies: over short timescales the recency effect is dominant while the contradicting effect was found over long timescales. Accordingly, the dominance of each of the effects is realized differently, dependent on the *actual temporal structure of the input*: Where no memory and structure exists in the input - the short timescale effect is dominant, while the main effect for correlated inputs is adaptation. This point is specifically relevant for lab experiments which use that common paradigm of shuffled input data - this regime influences the tendencies and moves the experiment away from its natural regime and balance. As natural experiences are in most cases slowly changing [32], this is a good reason to include correlated structures in the experimental design.

Cross modal interactions are context dependent In the second set of experiments we showed that the dynamic relations of the audio-visual detecting process point to complex interactions: Coordinated shifts of attention in the open loop turned, in the closed loop regime, into an adjacent process where the modalities become slightly correlated. This coordination occurred despite the controllers themselves not having any interactions. The rich literature concerning inter-modal interactions is full of examples regarding the relations between hearing and seeing. Our results demonstrate how specific contextual conditions and the framework of experiments exposes different relations, from the vast assortment of possible ones.

Cross modal interactions are (probably) asymmetric The second aspect of coordination between modalities was reflected in the level of fluctuations. Low fluctuations in auditory modality while it is clamped, tended to suppress fluctuations in the visual modality when it itself is in an open loop. Such influences are apparently mediated by a central process of the perceptual system. This tendency is asymmetric as the quenching of fluctuations is not applied to the auditory modality. Such asymmetry is in line with previous studies pointing to a stronger effect of auditory stimuli on visual perception and attention than the other way round [72, 60]. In studies that found bidirectional interactions these are usually related to a bound perception of an object that have both auditory and visual properties [44, 18].

Although the literature supports the asymmetry which we found, it is important to note: During experiments we had a suspicion that the auditory fluctuations were also influenced by the visual modality state. While this was the case for many subjects, the findings were always inconclusive. A hypothesis was raised that the asymmetry is actually an artifact, presumably resulting from the narrower dynamic range of the auditory stimuli (which, in turn, was a side-product of the specific parameters chosen for the closed loop controller). This hypothesis was neither rejected nor confirmed.

Inter-modal relations alter basic properties of perception In the bi-modal case the effect of recency did not exist: not between modalities, nor within them and even not in the case of pairs of consecutive stimuli in the same modality. This Is in contrast to the results obtained in the experiment of only visual stimuli. Generally, this difference in results between the similar, though different, paradigms demonstrates how important it is to consider as many contextual parameters as possible in psychophysical studies. Specifically, it shows that an admixture of two modalites in an experiment is not resulting with a simple addition of the effects found in one separated modality with the effects of another, it is much more complex than that.

We see that within a modality the contextual parameters may change the detection properties such that the recency effect could exist (in one modality paradigm) or not exist (in bi-modality paradigm). A derived conclusion is that recency of repsonses is a *cognitive effect* and not a sensory one. This outcome matches the design of the model that we have offered for one modality detection process, where indeed the recency effect was attributed to the cognitive part of perception. Altogether, this is an additional support for our claim that central mechanisms manipulate perception, and that the integration between detection processes of the different modalities is done away from the sensory path.

What appears to be a conflict may be resolved if we consider that mixing of modalities, thus raising the mental load of the trials, could alter properties of perception of each modality, for example it can diminish the ability to rely on history. In accordance, in these conditions, the sensitivity to *input* could be larger relative to the non-input related tendencies, i.e. the effects of the biases are reduced. This claim is in line with previous reports which suggest that as the mental effort gets higher, to some extent, the sensitivity to the stimulus is also raising, especially when distinct auditory and visual signals are presented concomitantly [16].

4.2 Methodological challenges, comments on the experiments and their analysis & deliberations

Ambiguity and the goal of perception This research is focused on repetitive weak visual/auditory signals. Weak signals were produced with low contrast to the background, resulting in ambiguous perceptual trials where the subject is not sure whether a stimulus existed or not. Subjects are instructed to resolve their ambiguity by giving one of two possible answers (a dichotomous answer) for each trial. There is an undergoing assumption that perceptual ambiguity is uncomfortable for the subjects. Thus, over and beyond their desire to follow the instructions they are also internally motivated to resolve the ambiguity, i.e. to be sure of what "the real physical truth" is. That is the reason we used "good" and "reliable" to describe the quality of perception when ambiguity is reduced.

However, this assumption is not backed up with anything beyond self-introspection. It might be that other internal motivations also guide the subject, and they may be contradictory to the first. Hypothetically, if a subject is intending (maybe unconsciously) to optimize information regarding all stimuli, then he may try to maintain some kind of 1-to-1 table of the real amplitudes delivered, realized in his psychometric curve. Such an internal motivation may result with an attempt to cover the dynamic range as much as possible. This may standardize a shallower psychometric curve as the ideal to strive for, suggesting that higher ambiguity may be "better". Technically, this option would require the ability to be aware of all of the history of the inputs, even those which were responded to with a "no". However, this is not completely unreasonable, considering the results found by my colleague Tal Knafo: She showed in a very similar paradigm that the threshold for detection revealed when monitoring eye movements is dramatically lower than that of the behavioral response, hence, there is some point in the detection path which contains that information.

Even without such assumptions it appears, as a general outcome, that seeking the origin of fluctuations is, to some extent, seeking for the general purpose and goal of perception. As we found a balancing mechanism between stability of perception and sensitivity to changes, which is presumably a part of our perception goals, some other types of internal motivations are probably also involved which are out of the scope of our measurements. For example, Marom & Wallach [38] put forward the hypothesis that there is an internal motivation to be in relations with the object. How such motivation, if it exists, alters response fluctuation is a question that remains unanswered.

Short signals limited analyses methods The experiments in this study were very demanding, and the difficulty restricted the number of repetitions a subject could perform. The compromise on short sessions was very costly in terms of our ability to analyze their properties. In the auditory-visual experiments, for example, a reasonable session length that subjects could complete was of around 300 trials. However, ignoring sham trails, dividing by 2 for each modality and cutting off part of the beginning to let the controller stabilize, we were left with much shorter signals.

Short signal set serious problems especially for computing dynamic measures: There were analyses which were borderline in their feasibility because of the signal length - such as extracting reliable parameters of sigmoid fits of psychometric curves. There were others that were completely non-informative - such as all types of spectral analyses (which are, theoretically, ideal for dynamic process appreciation).

Challenges in appreciation of dynamic features The dynamic approach dictated certain ways in which the experiments could be conducted, with these being different from many conventional experimental methods. A basic measure we used was a filtered responses: we termed it *momentary detection probability.* It became the standard measure for many of our analyses: we calculated its characteristics, and its relations with other signals. For instance, the level of fluctuations was quantified by its standard deviations.

But there is an important reservation regarding this "standard": the moment we filtered the inputs/outputs with a specific filter length τ we lost the freedom of multiple timescales, and could focus on a specific one. When it was possible and important, post processing calculations were done using various types and lengths of filters. But, this methodological limitation was especially prominent in the audio-visual experiment where, already in real-time during the closed loop sessions, inputs were regulated upon a specific filter that was applied to responses with a specific length. In several (not listed) experiment there were other filter lengths that were successively used for response clamp paradigms, however, in principal, it is possible that different filter properties might have emerged with somehow different results.

Closed loop - What does it really do? Beside the methodological problem of closing the loop using a specific filter there is a more general question regarding the use of this method. This behavioral closed-loop paradigm is relatively new and we are not yet certain of all its effects. The closed loop was designed to reduce fluctuation of response in order to investigate how this would be reflected in the controller, but this was not the only thing this regime influenced. The closed loop kept the subjects constantly in their most ambiguous area throughout the session, while in the open loop they experienced times where the stimuli were in a slightly more definite zone.

An additional assumption was that flattening the fluctuation by allowing the difficulty level to follow the momentary state of the subject will result in a somewhat more comfortable situation for the subjects, compared with the open loop condition. However, it appeared that some subjects do not feel more comfortable in this regime. In subject interviews that took place after each session contradicting views were expressed regarding the comfort rating of this session.

Maybe this is because in a closed loop, in the way that it was implemented, there is a constant rejection of prior expectations: each stimulus slightly contradicts the subjects' previous prediction. This rejection resulted in a typical high rate of response alternations in this regime, which is opposite to the inherent tendency of expecting continuity (reflected as low rate of alternations). And, even if the matter of comfort is not relevant, this is an extreme situation.

Challenges to the ability to model via experiment A general challenge in evaluating a phenomenon is being able to model it without neglecting crucial features. The experiments have to reliably reflect reality in a small measurable scale - preserving the features of life that are at the heart of the matter being investigated. The relations with the environment in this study are such a central issue, yet, unfortunately, no paradigm that we tested reflected it in perfectly realistic conditions. *Closed-Loop* sessions represented specific relations between the subject and the object, but these are extreme relations of consistent rejection; In all *Open-Loop* sessions this connection is completely missing; the stimulus is not affected at all by the viewer, at the most it is statistically related via a general natural-like rhythm (Pink/Brown), or not at all (White noise). Hence, all conditions are extreme points located on a frame surrounding the area in which (natural?) complex relationship exist. They represent only a few possible (extreme) situations, singular instances of relations one may experience. While the whole area inside the frame, where the vast majority of interesting natural phenomena are present, is out of reach in this research as in practically all other psychophysical studies.

Variability between/within subjects Large variability within and between subjects typical in psychophysics. There are numerous elements that can influence one's perceptual performance. So the different measurements either within one subject at different times or between different subjects have numerous degrees of freedom, where only few of them are controllable in experiments. This study deals with fluctuations in response, so obviously this issue was considered, but despite this it was still a major challenge, which affected much of what we could conclude.

As a rule of the thumb - differences among people are larger than those within one person during an hour of experiments. Specifically, in our experiments, having assumed that different people would tend to have different points of balance and different thresholds, we compared each subjects' properties only with his or her own results in the different sessions. Later we compared the trends to establish the overall statistics. However, sometimes the variability of trends was also rather high.

Most of the subjects indeed tended to maintain some amount of stability in their performance, but some fluctuated quite a lot. Apparently, some uncontrolled factor was expressed in variability when longer time-scales were involved. This factor apparently made these subjects change their "center" or their tendency to fluctuate, which in turn could alter their results (detection rate or standard deviation) and, worse, it could also influence the measurements' meanings. The possible consequences of such a change may be explained in the following example: If a subject had certain fluctuations levels centered around a particular threshold, and later this subject's responses were centered around a very different level, distant to the dynamic range - it is possible that this "fluctuations level" around this new level, mean something different to that which they meant before.

A few attempts were made to test the hypothesis that some long term effects changed individual trends. These included separating the subjects into groups according to the consistency of their fluctuations' levels between the open loop sessions, or according to the size of the threshold changes, and then comparing between the groups' performances. The attempts were not conclusive, presumably because of the rather small number of subjects in the groups making it hard to firmly establish such tendencies. In summary, it appears that results would have been much more significant if all subjects behaved somehow "normally". But, they don't... so, probably this is another part of the conclusion - that trends in psychophysics only reflect those who "behave well" and especially when they are stable enough to be measured and evaluated. Even when fluctuations are of interest.

Variability in instructions In addition to the issues discussed above, the experiments' subjects were also very sensitive to instructions, which were given orally; On notable example is that some subjects, who were not specifically instructed to prefer "no" for "yes" if they were entirely unsure as to whether they detected the signal or not, tended to have much higher false positive errors. Some of them had to be excluded from analysis, as mentioned in the methods chapters.

Summary As pointed out, there are many imperfections and compromises in the methodology and operation of the experiments in this thesis. In addition, there are some inconclusive results as well as prior assumptions that were not sufficiently established. However, despite these flaws it may be concluded that the results show how biases and balances, relations and context are summed up to a coherent picture reliably describing the behavior of fluctuations in response to weak stimuli. The study demonstrates how, already in a primary stage of sensing, predictions are made and how these influence the perception processes. The existence of such effects in an elementary task imply that the perceptual level is relevant to the understanding of basic human-world relations.

Chapter 5

Open questions and future study

This research focused on the inspection of response fluctuations from a dynamic perspective. The influence of temporal history and of the relations between modalities in adult human subjects were examined. Some issues were unfortunately left unanswered, and some results elicited additional interesting questions beyond this study's scope.

5.1 Some open questions

In the analysis we encountered several issues that were not conclusive, some of them were mentioned before, here we list the main ones:

From the first experiment we were left with the open question regarding the adaptation bias source. Adaptation, as we showed is most likely to affect the sensory path, but is it based on the input levels or the output responses, or both? Since there is a high correlation between the inputs and the outputs this is a question which is very hard to answer. May be it should be addressed by designing a specially dedicated experiment.

Another issue that has been left open is related to the second experiment. As mentioned in the discussion, the asymmetry that was found between the modalities might actually be a result of the specific experimental conditions. Although the work of audition research of Bekesy and his followers performed in closed-loop, yet the control of fluctuation in the method that we use is less studied in hearing than in vision. Perhaps it would be worth exploring whether different choice of parameters of the controller would elicit different relations between hearing and seeing. A promising point at which to start to answer this question is finding a set of parameters that would result in a less tight clamp, especially for the auditory part.

It also could be beneficial to broaden the understanding regarding the influence of a closed loop procedure in order to better understand all of its effects. The results derived from using this procedure could then be interpreted more solidly.

5.2 Ideas for broadening the results and future directions

In the study we inspected the temporal structure of changing amplitudes. There are other properties that could be changed like the tone level (pitch) and the length of the auditory signal or shape and size of the visual spot. Similar experiments examining the changes of these features may broaden the scope of our conclusions.

It would also be very interesting to investigate the developmental aspects of perception. Testing children of different ages may shed light on the development of the biases of elementary sensory perception.

Other conditions are also may intervene with these perceptual processes as cognitive pathologies. Specifically, it would be interesting to check whether conditions of attention deficits alter the relations between the modalities in a closed or open loop.

There is also the possibility to test if combination of two other modalities (ex. audition and tactile) would yealid somehow similar results.

5.3 Summary

The dynamic perspective and the tools of analysis that were developed may be useful for designing a variety of psychophysical experiments and offer interesting opportunities for future research.

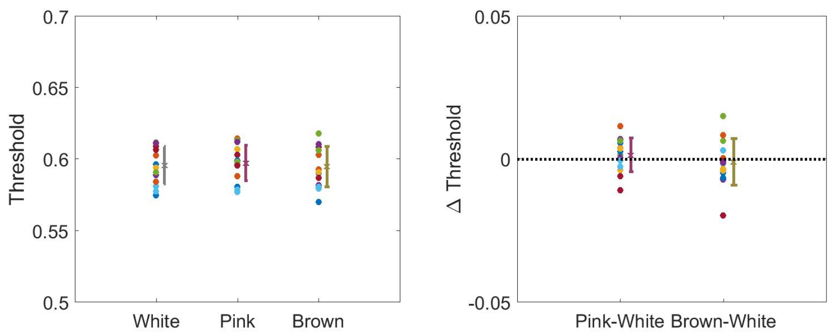
Appendix A

More results & Negative results

A.1 Appendix1: Additional results for Visual experiment

A.1.1 No change in threshold of psychometric curve in correlated inputs

Comparing all and individual thresholds of psychometric curves we see no change in threshold throughout experiment sessions.



(a) ThresholdAll (b) ThresholdAll

Figure A.1: **No change in threshold** between "white", "Pink" and "Brown".

A.1.2 POA in instantaneous model is not sensitive to the sessions slope

Comparison POA of between the real subjects and 15 model subjects, similar to what is described in 2.2.2. The difference is that in this instantaneous model slopes of all 3 session types were the same ($Slope = 30$). Different POAs between sessions are not explained by the difference in slopes reported to characterize the 3 temporal regimes (as reported in 2.2.1).

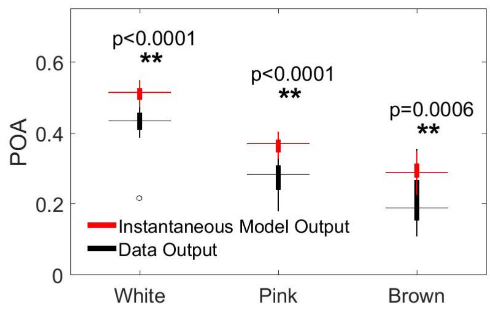


Figure A.2: **POA is not sensitive to the different sessions slope** -the gap betewen probabilty of real subjects POAs and the model POAs is always around 0.08.

A.1.3 Cognitive model

A.1.3.1 Cognitive model description

The cognitive model means that biases are modeled in post-sensory stage of processing. On the basis of an instantaneous model, a constant input-output sigmoid function, two types of history dependent biases are added, both dependent on the history of votes. The dependence on history manifests a balance between forces of constant positive recency in short term and adaptation (see equation A.1). A significant difference from the first sensory-cognitive combined model is that the calculation of the adaptation biases is dependent only on the history of responses, not on the input history.

In the model both biases are added to the instantaneous probability and than the modulated probability is compared to a stochastic binary value which is being ruffled.

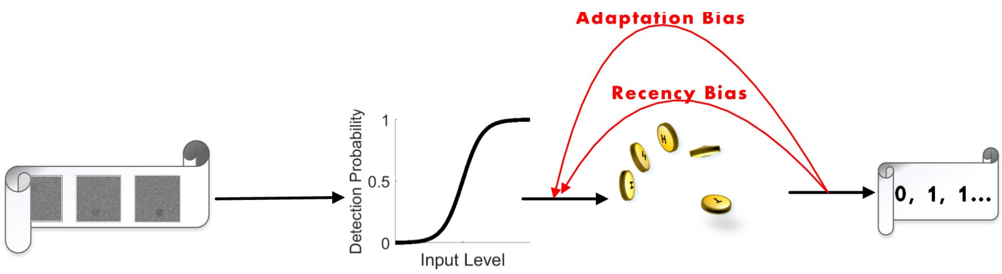


Figure A.3: **The cognitive model** Sensory process is instantaneous and independent on history. It is modeled by constant sigmoidal relations between the momentary input level and the probability of the coin flip. The cognitive process, on the other side, encapsulates all contextual dependencies. The probability of the coin flip is a weighting of 3 probabilities the instantaneous with the two biases that depend on the history of responses.

A.1.3.2 Cognitive model details

1. **Instantaneous Probability** - *pi* - is calculated for each input level using a sigmoid function of fixed parameters: *Sl.* & *Th.* that represent the slope and the threshold respectively (equation A.3). The parameters *Sl.* & *Th.* that were

used in the model were the average parameters found to characterize the human subjects; Specifically $Sl.$=30, $Th.$=0.595.

2. **Recency Bias Probability** pr - is implemented by a constant: Rc is dependent only on the previous vote. The constant is added if the previous vote was '1' and decreased in case it was '0' (equation A.4).
In the model Rc=0.1[probability].

3. **Adaptation Bias Probability** pb - implemented as a linear "spring" which works to balance history towards 0.5 detection probability.

   History of outputs is represented by filtered value of previous votes. The filter is an exponentially decreasing filter, which means that the recent votes counts more than the further ones (equation A.5b). The decay of the filter is characterized by a constant τ.
   In the model τ=32[time steps].

   The bias grows linearly as the filtered history of votes getting farther from 0.5. The distance between 0.5 and history detection probability is multiplied by a constant: Ac (equation A.5a).
   In the model Ac=0.2[probability multiplier].

   Note: The adaptation bias can be either positive or negative. For example: if recent history of votes contained many '1's, the detection probability value is higher than 0.5, therefore the delta $(0.5 - y_i)$ is negative and the adaptation bias will decrease probability for next vote to be '1'.

$$p_i(y_i = 1 \mid x_i,\, y_{i-1},\, F(y_{i-1})) = pi_i + pr_i + pa_i \tag{A.1}$$

$$y_i = \begin{cases} 0 & if \quad z_i < p_i \\ 1 & if \quad z_i \geqslant p_i \end{cases} \tag{A.2}$$

.

$$pi_i = \frac{1}{1 + 10^{Sl.*(x_i - Th.)}} \tag{A.3}$$

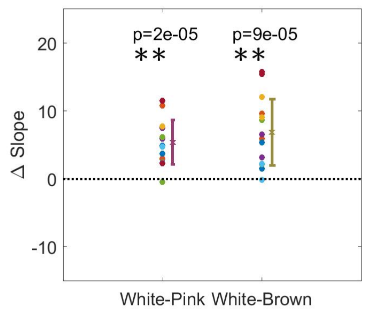
$$pr_i = \begin{cases} Rc & if \quad y_{i-1} = 1 \\ -Rc & if \quad y_{i-1} = 0 \end{cases} \tag{A.4}$$

$$pr_i = Ac * (0.5 - F(y_{i-1})) \tag{A.5a}$$

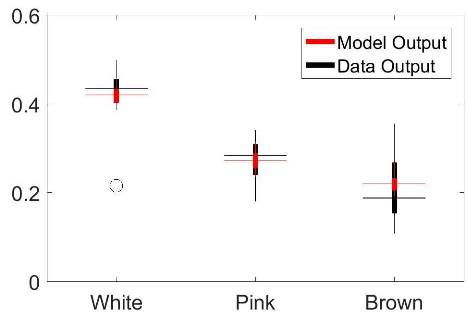
$$F(y_i) = y_i * (1 - e^{\frac{1}{\tau}}) + F(y_{i-1}) * (e^{\frac{1}{\tau}}) \tag{A.5b}$$

A.1.3.3 Cognitive model performance

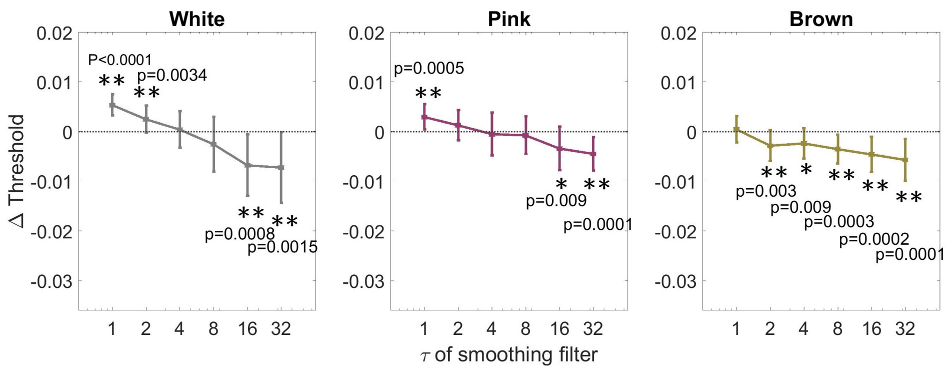
Analysis of 15 model subjects using the all cognitive model shows that this model is a valid option to describe the data.



(a) Slope change



(b) POA



(c) Hysteresis

Figure A.4: **Cognitive model Performance** (a) - The model show the expected elevation in the slope of *Pink* and *Brown* relative to slope in *White* (b) - the probabilities of alternation in the different modes are reproduced in model subjects. (c) - the relation between raising and falling psychometric curves with respects to the different timescales in the model is very similar to the actual data (compare to figure 2.11c).

Bibliography

[1] Arman Abrahamyan, Laura Luz Silva, Steven C. Dakin, Matteo Carandini, and Justin L. Gardner. Adaptable history biases in human perceptual decisions. *Proc. Natl. Acad. Sci.*, 113(25):E3548–E3557, jun 2016.

[2] David Alais, Concetta Morrone, and David Burr. Separate attentional resources for vision and audition. *Proc. R. Soc. B Biol. Sci.*, 273(1592):1339–1345, jun 2006.

[3] H. Norman Anderson. Test of adaptation-level theory as an explanation of a recency effect in psychophysical integration. *J. Exp. Psychol.*, 87(1):57–63, 1971.

[4] David L Barack and Joshua I Gold. Temporal trade-offs in psychophysics. *Curr. Opin. Neurobiol.*, 37:121–125, apr 2016.

[5] Jan Benda and Andreas V M Herz. A Universal Model for Spike-Frequency Adaptation.

[6] H. Richard Blackwell. Studies of Psychophysical Methods for Measuring Visual Thresholds. *J. Opt. Soc. Am.*, 42(9):606, sep 1952.

[7] Anne-Marie Bonnel and Ervin R Hafter. Divided attention between simultaneous auditory and visual signals. *Percept. Psychophys.*, 60(2):179–190, 1998.

[8] Naama Brenner, William Bialek, and Rob de Ruyter van Steveninck. Adaptive Rescaling Maximizes Information Transmission. *Neuron*, 26(3):695–702, 2000.

[9] Niko A Busch, Julien Dubois, and Rufin Vanrullen. The Phase of Ongoing EEG Oscillations Predicts Visual Perception. *J. Neurosci.*, 29(24):7869–7876, 2009.

[10] Adrien Chopin and Pascal Mamassian. Predictive Properties of Visual Adaptation. 2012.

[11] Colin W. G. Clifford, Peter Wenderoth, and Branka Spehar. A functional angle on some after-effects in cortical vision. *Proc. R. Soc. London B Biol. Sci.*, 267(1454), 2000.

[12] Jonathan D Cohen, Samuel M McClure, and Angela J Yu. Should I stay or should I go? How the human brain manages the trade-off between exploitation and exploration. *Philos. Trans. R. Soc. B Biol. Sci.*, 362(1481), 2007.

[13] Tom N. Cornsweet. The staircrase-method in psychophysics. *Am. J. Psychol.*, 75(3):95–106, 1962.

[14] David V Cross. Sequential dependencies and regression in psychophysical judgments. *Percept. Psychophys.*, 14(3):547–552, 1973.

[15] S V David, W E Vinje, and J L Gallant. Natural Stimulus Statistics Alter the Receptive Field Structure of V1 Neurons. *J. Neurosci.*, 24(31):6991–7006, 2004.

[16] D R Davies, Lesley Lang, and V J Shackleton. THE EFFECTS OF MUSIC AND TASK DIFFICULTY ON PERFORMANCE AT A VISUAL VIGILANCE TASK. 64(3):383–389, 1973.

[17] Nathaniel D Daw, John P O'Doherty, Peter Dayan, Ben Seymour, and Raymond J Dolan. Cortical substrates for exploratory decisions in humans. *Nature*, 441(7095):876–9, jun 2006.

[18] Jon Driver and Charles Spence. Crossmodal attention. *Curr. Opin. Neurobiol.*, 8(2):245–253, 1998.

[19] J Duncan, S Martens, and R Ward. Restricted attentional capacity within but not between sensory modalities. *Nature*, 387(6635):808–810, 1997.

[20] R Duncan Luce, Robert M Nosofsky, David M Green, and Albert F Smith. The bow and sequential effects in absolute identification. *Percept. Psychophys.*, 32(5):397–408, 1982.

[21] Howard E Egeth and Steven Yantis. Visual Attention: Control, Representation, and Time Course. *Annu. Rev. Psychol*, 48:269–97, 1997.

[22] E Eijkman and A J H Vendrik. Can a Sensory System be Specified by Its Internal Noise? *J. Acoust. Soc. Am.*, 37(6):1102, 1965.

[23] Andreas K. Engel and Wolf Singer. Temporal binding and the neural correlates of sensory awareness. *Trends Cogn. Sci.*, 5(1):16–25, 2001.

[24] Thomas K. Ferris and Nadine B.. Sarter. Cross-Modal Links Among Vision, Audition, and Touch in Complex Environments. *Hum. Factors*, 50(1):17–26, 2008.

[25] Jason Fischer and David Whitney. Serial dependence in the perception of faces. *Curr. Biol.*, 24(21):2569–2574, 2014.

[26] Albert D. Freiberg. 'Fluctuations of Attention' with Weak Tactual Stimuli: A Study in Perceiving. *Am. J. Psychol.*, 49(1):23–36, oct 1937.

[27] Asaf Gal and Shimon Marom. Entrainment of the intrinsic dynamics of single isolated neurons by natural-like input. *J. Neurosci.*, 33(18):7912–791872, 2013.

[28] Sergei Gepshtein and Michael Kubovy. Stability and change in perception: spatial organization in temporal context. *Exp. Brain Res.*, 160(4):487–495, jan 2005.

[29] J. J. Gibson and M. Radner. Adaptation, after-effect and contrast in the perception of tilted lines. I. Quantitative studies. *J. Exp. Psychol.*, 20(5):453–467, 1937.

[30] David L. Gilden and Gray Wilson Stephanie. On the nature of streaks in signal detection. *Cogn. Psychol.*, 28(1):17–64, 1995.

[31] Morris K. Holland and G. R. Lockhead. Sequential effects in absolute judgments of loudness. *Percept. {&} Psychophys.*, 3(6):409–414, nov 1968.

[32] H. L. Hollingworth. The Central Tendency of Judgment. *J. Philos. Psychol. Sci. Methods*, 7(17):461, aug 1910.

[33] C. I. Howarth and M. G. Bulmer. Non-random sequences in visual threshold experiments. *Q. J. Exp. Psychol.*, 8(4):163–171, 2016.

[34] Jennifer A. Johnson and Robert J. Zatorre. Attention to simultaneous unrelated auditory and visual events: Behavioral and neural correlates. *Cereb. Cortex*, 15(10):1609–1620, jan 2005.

[35] Jennifer A. Johnson and Robert J. Zatorre. Neural substrates for dividing and focusing attention between simultaneous auditory and visual events. *Neuroimage*, 31(4):1673–1681, 2006.

[36] Christoph Kayser, Konrad P. Körding, and Peter König. Processing of complex stimuli and natural scenes in the visual cortex. *Curr. Opin. Neurobiol.*, 14(4):468–473, 2004.

[37] G. R. Lockhead and G. R. Identification and the form of multidimensional discrimination space. *J. Exp. Psychol.*, 85(1):1–10, 1970.

[38] Shimon Marom and Avner Wallach. Relational Dynamics in Perception: Impacts on Trial-to-trial Variation. *Front. Comput. Neurosci.*, 5(April):16, 2011.

[39] Gerrit W. Maus, Wesley Chaney, Alina Liberman, and David Whitney. The challenge of measuring long-term positive aftereffects. *Curr. Biol.*, 23(10):R438–R439, may 2013.

[40] William J Mcgill. Serial effects in auditory threshold judgments. *J. Exp. Psychol.*, 5(53):297, 1957.

[41] Harry McGurk and John MacDonald. Hearing lips and seeing voices. *Nature*, 264(5588):746–748, 1976.

[42] S. Monto, S. Palva, J. Voipio, and J. M. Palva. Very Slow EEG Fluctuations Predict the Dynamics of Stimulus Detection and Oscillation Amplitudes in Humans. *J. Neurosci.*, 28(33):8268–8272, 2008.

[43] K. Narendra and P. Gallman. An iterative method for the identification of nonlinear systems using a Hammerstein model. *IEEE Trans. Automat. Contr.*, 11(3):546–550, jul 1966.

[44] Ann O'Leary and Gillian Rhodes. Cross-modal effects on visual and auditory object perception. *Percept. Psychophys.*, 35(6):565–569, 1984.

[45] J. Matias Palva and Satu Palva. Infra-slow fluctuations in electrophysiological recordings, blood-oxygenation-level-dependent signals, and psychophysical time series. *Neuroimage*, 62(4):2201–2211, oct 2012.

[46] Allen Parducci. Sequential effects in judgment. *Psychol. Bull.*, 61(3):163–167, 1964.

[47] Allen Parducci and Arthur Sandusky. Distribution and sequence effects in judgment. *J. Exp. Psychol.*, 69(5):450–459, 1965.

[48] Frederike H Petzschner and Stefan Glasauer. Iterative Bayesian estimation as an explanation for range and regression effects: a study on human path integration. *J. Neurosci.*, 31(47):17220–17229, 2011.

[49] Irwin Pollack. Intensity Discrimination Thresholds under Several Psychophysical Procedures. *J. Acoust. Soc. Am.*, 26(6):1056, 1954.

[50] Michael I Posner, Charles R R Snyder, and Brian J Davidson. Attention and the detection of signals. *J. Exp. Psychol. Gen.*, 109(2):160–174, 1980.

[51] Ofri Raviv, Merav Ahissar, and Yonatan Loewenstein. How Recent History Affects Perception: The Normative Approach and Its Heuristic Approximation. *PLoS Comput. Biol.*, 8(10), 2012.

[52] Vincenzo Romei, Benjamin De Haas, Robert M. Mok, and Jon Driver. Auditory stimulus timing influences perceived duration of co-occurring visual stimuli. *Front. Psychol.*, 2(SEP):1–8, 2011.

[53] Daniel L Ruderman and William Bialek. Statistics of natural images: Scaling in the woods Phys. *Adv. Neural Inf. Process. Syst.*, 73(6):551–558, 1994.

[54] Caspar M Schwiedrzik, Christian C Ruff, Andreea Lazar, Frauke C Leitner, Wolf Singer, and Lucia Melloni. Untangling perceptual memory: hysteresis and adaptation map into separate cortical networks. *Cereb. cortex*, 24(5):1152–64, may 2014.

[55] Daniel Senkowski, Till R. Schneider, John J. Foxe, and Andreas K. Engel. Cross-modal binding through neural coherence: implications for multisensory processing. *Trends Neurosci.*, 31(8):401–409, aug 2008.

[56] Tatyana Sharpee, Nicole C. Rust, and William Bialek. Analyzing Neural Responses to Natural Signals: Maximally Informative Dimensions. *Neural Comput.*, 16(2):223–250, 2004.

[57] Muzafer Sherif, Daniel Taub, and Carl I. Hovland. Assimilation and contrast effects of anchoring stimuli on judgments. *J. Exp. Psychol.*, 55(2):150–155, 1958.

[58] Joel S Snyder, Caspar M Schwiedrzik, A Davi Vitela, and Lucia Melloni. How previous experience shapes perception in different sensory modalities. *Front. Hum. Neurosci.*, 9:594, 2015.

[59] Salvador Soto-Faraco, Charles Spence, and Alan Kingstone. Cross-modal dynamic capture: congruency effects in the perception of motion across sensory modalities. *J. Exp. Psychol. Hum. Percept. Perform.*, 30(2):330–45, 2004.

[60] C Spence and J Driver. Audiovisual links in endogenous covert spatial attention. *J. Exp. Psychol. Hum. Percept. Perform.*, 22(4):1005–1030, 1996.

[61] Joseph C. Stevens and Lawrence E. Marks. Cross-modality matching of brightness and loudness. *Proc. Natl. Acad. Sci.*, 54:407–411, 1965.

[62] S. S. Stevens and Hilda B. Greenbaum. Regression effect in psychophysical judgment. *Percept. Psychophys.*, 1(12):439–446, dec 1966.

[63] Mark Steyvers, Michael D. Lee, and Eric-Jan Wagenmakers. A Bayesian analysis of human decision-making on bandit problems. *J. Math. Psychol.*, 53(3):168–179, jun 2009.

[64] M.M. Taylor, P.H. Lindsay, and S.M. Forbes. Quantification of shared capacity processing in auditory and visual discrimination. *Acta Psychol. (Amst).*, 27:223–229, 1967.

[65] Bernhard Treutwein. Adaptive psychophysical procedures. *Vision Res.*, 35(17):2503–2522, 1995.

[66] E Tulving, P. H. Lindsay, and I ' H Lindsay. Identification of simultaneously presented simple visual and auditory stimuli. *Acta Psychol. (Amst).*, 27(0):101–109, 1967.

[67] Leendert van Maanen, Scott D. Brown, Tom Eichele, E.-J. Eric-Jan Wagenmakers, Tiffany Ho, John Serences, and Birte U. Forstmann. Neural Correlates of Trial-to-Trial Fluctuations in Response Caution. *J. Neurosci.*, 31(48):17488–17495, 2011.

[68] William S Verplanck, George H Collier, and John W Cotton. Nonindependence of successive responses in measurements of the visual threshold. *J. Exp. Psychol. , Am. Psychol. Assoc.*, 44(4):273, 1952.

[69] William E Vinje and Jack L Gallant. Natural Stimulation of the Nonclassical Receptive Field Increases Information Transmission Efficiency in V1. *J. Neurosci.*, 22(7):2904–2915, 2002.

[70] Eric-Jan Wagenmakers, Simon Farrell, and Roger Ratcliff. Estimation and interpretation of l/f alpha noise in human cognition. *Psychon. Bull. Rev.*, 11(4):579–615, 2004.

[71] Lawrence M. Ward. Repeated magnitude estimations with a variable standard: Sequential effects and other properties. *Percept. {&} Psychophys.*, 13(2):193–200, jun 1973.

[72] LM Ward. Supramodal and Modality-Specific Mechanisms for Stimulus-Driven Shifts of Auditory and Visual Attention. *Can. J. Exp. Psychol.*, 48(2):242, 1994.

[73] M Wertheimer. An investigation of the randomness of threshold measurements. *J. Exp. Psychol.*, 45(5):294–303, 1953.

[74] B. J. West and M Shlesinger. The Noise in Natural Phenomena. *Am. Sci.*, 78(1):40–45, 1990.

[75] Yuguo Yu, Richard Romero, and Tai Sing Lee. Preference of sensory neural coding for 1/f signals. *Phys. Rev. Lett.*, 94(10):18–21, 2005.

[76] Barbara Zoeke, Viktor Sarris, and Giovanni Hofer. Comparative Psychophysics: Some Contextual Effects in Birds and Humans. *Int. J. Comp. Psychol.*, 3(2), 1989.

בנוסף שהראינו גם כי מאפייני התפיסה הספציפיים של אופנות אחת יכולים להשתנות כאשר מעורבות אופניות נוספות. דבר זה מדגיש את הכרח להתיחס לכלל ההקשרים בהם נמדדים תהליכי תפיסה, ולאופן בו הם ומנותחים ומפורשים.

סיכום

במחקר זה נבחנו השפעת של ההקשרים על תנודתיות התגובות לגירויים חלשים. בחלק אחד ההקשרים היו זמניים - של תלות בהיסטוריה של הגירויים ו/או התגובות הקודמות, ובחלק השני ההקשרים היו בין החושים השונים. סך כל הממצאים מהווים אישוש לסברה שמעורבות של פעילות קוגניטיבית תורמת להיווצרות תנודות ברצפי התגובות, ואיזונים של הטיות שונות ביחס להיסטוריה מהווים באופן חלקי הסבר למבנים הסדורים שנמצאים בתגובות אלו. הטיות שונות באות לידי ביטוי כתלות באופן עריכת הניסוי ולפיכך בניסויים פסיכופיזיים יש חשיבות רבה להתיחס לפרמטרים של הקשרי הסביבה, זמניים ואחרים, על מנת לפרש את הממצאים.

מלבד הממצאים עצמם, נקודת המבט הדינמית של המחקר תרמה לפיתוח שיטות המאפשרות התבוננות על יחסי תגובה - גירוי - הקשר וזאת על פני תחומי זמן שונים. שיטות אלו והיבט זה לכשעצמו מהוים חידוש בתחום.

ומצד שני נוטה לאזן את הנטיה הכללית של היסטוריית תגובותיו. ניתן להפריד את הנטיות לפי התיחסותן לתחומי זמן אחרים בקשר להיסטוריה: ביחס להיסטוריה קצרה נטיה להמשיך, וביחס לארוכה לאזן. הראנו שהנטייה להמשיך כמו בתגובה קודמת היא בעלת מידה קבועה שאינה תלויה במאפייני הכניסה, אבל האיזון בין שתי הנטיות המנוגדות הינו שונה כתלות במשטר שינויי הכניסה: שינויים מהירים ידגישו את הנטיה להמשיך (קצרת הזמן), ואילו שינויים איטיים את הנטיה לאזן את ההיסטוריה (הארוכה יותר). ניסחנו מודל מתימטי כללי המציג את האיזון בין ההטיות, ואנו מציגים אשרור של תוצאותיו בהשוואה תוצאות הניסוי. הצגנו מספר גרסאות של המודל עם פירוט של הנקודות לטובת כל גרסה ונגדה.

הנטיות השונות ניתנות לפירוש כהסתגלות המייצבת את התפיסה מול שינוים מהירים ועידוד גישוש (אקפלורציה) כאשר השינוים איטיים. איזון בין התסגלות לנטיה לגישוש מוכרת היטב מתחומים של קבלת החלטות ובשנים האחרונות אף במנגנונים תאיים ורשתות תאים. כאן היא מובאת בהקשר של התפיסה חושית.

יחסי הגומלין בין תנודתיות התגובות הראייתיות והתגובות השמיעתיות

בחלק השני נחקרו היחסים בין תנודתיות התפיסה החושית של שתי אופנויות - ראיה ושמיעה, בשל הקשרים הקוגניטיביים הידועים בינהן. בניסוי שערכנו כל חזרה כללה הצגת רקע בשתי האופנויות באופן בו זמני אך רק באחת מהן, באופן אקראי, גירוי הופיע על פני הרקע. באופן זה הנבדק צריך להישאר עירני לשתי האופנויות אך הגירויים מופרדים. לצורך חקר יחסי הגומלין רתמנו כלי לוויסות מידת התנודתיות - בקר המרסן בחוג סגור את התגובות. הבקר כוונן ליצור הידוק של התגובות סביב הסתברות גילוי של 50%. הבקר קבע את עצמת הגירוי הבא על בסיס חיזוי הסתברות הגילוי הרגעית, המוסקת מתוך תגובות העבר. למשל: אם לנבדק קל לאחרונה לשמוע את הגירוי - הגירוי השמיעתי הבא יהיה חלש, וקשה יותר לזיהוי. בקר זה יצר יחסים בין האובייקט לנבדק. במחקר זה נעשה שימוש בחוג סגור לריסון תנודתיות של גירויים שמיעתיים בפעם הראשונה. בפרק הראשון של הניסוי השתמשנו בשני בקרים - אחד לכל אופנות, ללא קשר בינהם. בשלשה פרקים נוספים של הניסוי היה בקר רק באחת האופנויות והשניה בחוג פתוח או שלא היה כלל. כאשר אופנות מסויימת בחוג פתוח מוצגים הגירוים ב"שידור חוזר" על פי סדר העוצמות שנקבע על ידי הבקר בחוג הסגור הראשון.

ארבע פרקים אלו נתנו פתח לחקר היחסים בין התנודתויות של האופנויות. כאשר נבדקה השפעת הריסון של אופנות אחת על התנודתיות של האופנות השניה, שאינה מרוסנת מצאנו שישנה א-סימטריה ביחסים: ריסון התנודתיות של התגובות השמיעתיות דיכא את עוצמת התנודתיות של התגובות הראייתיות אך ללא שינוי בכיוון השני. בנוסף חקרנו את מידת ההתאמה)קורלציה(הזמנית-רגעית של התנודות בין האופנויות ומצאנו יחסים מורכבים: כאשר ראיה ושמיעה היו שתיהן בחוג פתוח, ללא יחסים עם האובייקט, נמצאו תנודות מנוגדות בכיוונן)קורלציה הפוכה(. אנו פירשנו יחסים הופכיים אלו כמשמרות בקשב - פעם קשב רב יותר ניתן לשמיעה ופעם לראיה. אולם, התמונה התהפכה כאשר שתי האופנויות היו בחוג סגור, ביחסים עם האובייקט, אע"פ שבין שני הבקרים לא היה קשר, התגובות הראו מידה מסויימת של סנכון. קשרים אלו בין האופנויות מאששים את הסברה שמנגנון קוגניטיבי גבוה הינו בעל השפעה על התנודתיות.

תקציר

מחקר פסיכופיזי זה עוסק בתפיסה ראשונית ־ ומתייחס לפער בין הגירוי הפיזי לתחושה הסובייקטיבית שהוא מעורר. העבודה מתמקדת בתנודתיות התגובה לגירוים חלשים, שמיעתיים וראייתיים.

תנודתיות בתגובה משמעותה היא שלאותו גירוי חלש, על גבול יכולת התפיסה, המוצג באופן חוזר יגיב נבדק באופן שונה בכל פעם. רצף התגובות לגירוי כזה כולל מאפינים מבניים ובעל חוקיות פונקציונלית המרמזים על כך שתנודתיות זו אינה רק "רעש מכונה" שנלוה לעיבוד החושי הראשוני, אלא בעל משמעות וקשר לפעילות קוגניטיבית גבוהה.

מחקר זה מתמקד בהיבטים דינמיים של התגובתיות. ההיבט הדינמי מתבטא בעקרון הכללי בו רצף התגובות ורצף הגירויים מתיחסים זה לזה בשלמותם, במקום להתיחס לתגובה בודדת עבור גירוי יחיד כמקובל. היבט כזה הינו יוצא דופן בקרב מחקרים בנושא ולכן נעשה שימוש בשיטות ניסוי שונות מהרגיל. בהתאם, פיתחנו גם מהלכי ניתוח נתונים מותאמים באופן יחודי להיבטים הדינמים, תוך שמגבלות שיטות אלו הובאו בחשבון.

בעבודה זו נחקרה הדינמיקה של התגובות התפיסתיות בשני מסלולים: בדרך ישירה ־ על ידי שינוי המאפינים הזמניים של מבנה גירויי הכניסה, ובדרך עקיפה ־ בהתבוננות ביחסי הגומלין בין תגובות ראייתיות לתגובות שמיעתיות.

תנודתיות כתלות במאפינים הזמניים של מבנה גירויי הכניסה

על מנת לחקור את ההקשר הזמני שבו הגירויים מוצגים בחרנו להתיחס לשינויי עצמה של אות הכניסה סביב סף החישה. הצגנו לנבדק שלוש פעמים אות כניסה הנלקח מאותה התפלגות סביב סף החישה, כאשר בכל פעם משטר השינוי בין הגירויים הוא אחר: פעם אחת עצמות משתנות מגירוי לגירוי באופן אקראי חסר זכרון, בקיצוניות השניה באופן המשתנה לאט מאוד ובתחום הביניים באופן משתנה לאט, אך פחות. בחירה במשטרי שינוי אלו באה לדמות מאפיינים של מצבים טבעיים בהם רוב השינויים הם איטיים, ולהשוותם לדרך בה מנוהלים מחקרים רבים בסדר גירויים אקראי.

בדרך זו מצאנו שישנה הקטנה של תחום אי־הודאות ככל שהשינויים איטיים יותר, פרשנות אפשרית לכך היא שהתפיסה מהימנה יותר עבור גירויים המשתנים לאט יותר. מצאנו שלנבדק ישנת הטיות התלויות בהיסטוריה של הגירוי ו/או התגובות הקודמות. הטייה מוגדרת לצורך זה כהגדלת ההסתברות להגיב בדרך מסויימת שאינה תלויה ישירות בעצמת הגירוי הנוכחי. על הנבדק פועלות שתי הטיות בכיוונים מנוגדים ־ מצד אחד הנבדק נוטה להמשיך להגיב כמו שהגיב בפעם הקודמת

המחקר בוצע בהנחייתם של פרופ' נעמה ברנר ופרופ' שמעון מרום, בפקולטה לרפואה.
פרופ' נעמה ברנר הינה חברת סגל בפקולטה להנדסה כימית.
פרופ' שמעון מרום הינו חבר סגל בפקולטה לרפואה.

ציון אם העבודה פורסמה בכתבי עת או הוצגה בכנסים. הרשימה תכתב בהתאם לכללי הציטוט (כולל הכותר ושמות השותפים). במקרה של שיתוף פעולה, פירוט תרומת המגיש.

תודות

שלמי־התודה של המחבר.

הכרת תודה מסורה לטכניון על מימון מחקר זה.

היבטים דינמיים של השפעות ההקשר על תפיסה חזותית ושמיעתית
מחקר פסיכופיזי

חיבור על מחקר

לשם מילוי חלקי של הדרישות לקבלת התואר
דוקטור לפילוסופיה

עורית גורדון

הוגש לסנט הטכניון – מכון טכנולוגי לישראל
אלול התשע"ז   חיפה   ספטמבר 2017

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מחקר פסיכופיזי

עורית גורדון