Computational Mechanisms of Sensorimotor Control

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Abstract. Inherent problems in sensorimotor control impair our ability to perform movements and react to our environment. Even though these problems are present sensoric and motoric ability of humans are outstanding. This is due to the fact that several computational mechanisms are used. Multisensory integration and forward models are such mechanisms that are also supported by evidence.

1 Introduction

The human ability to perform complex motor task and react is outstanding even in the face of several inherent problems in motor control. Computational strategies to overcome these problems are subject of this paper.

1.1 Problems in Motor Control

There are several problems for the motor system on order to perform skilled and efficient movements. The main problems are nonlinearity, nonstationarity, delays, redundancy, uncertainty, and noise[1]. This paper will shortly describe delays, noise and uncertainty and will present selected strategies how the sensorimotor system deals with these issues.

1.1.1 Noise

Noise is always present in the nervous system and influences sensory pathways as well as motoric pathways[2]. Noise occurs at all stages of sensorimotor control, from sensory processing to planning and to the execution of motor commands. Sensory noise is responsible for variability in estimating both internal states of the body and external states of the world. Noise also limits the ability to plan movements which leads to variability in movement endpoints [3] [4]. Furthermore it accounts for neuronal variability of cortical neurons that can predict future kinematic variability in reaching [5]. Additionally, variability of movements can arise due to noise in motor commands [6]. Importantly, the noise in motor commands seems to increase with the level of the motor command [7] [8]. This is called signal-dependent noise

1.1.2 Delays

There are delays in every stage of our sensorimotor system, starting from the delay in receiving afferent sensory information, to the delay in the neuromuscular system when executing efferent motor commands. Feedback of sensory information is contemplated by delays that are arising from receptor dynamics and conduction delays on nerve fibers and synaptic relays. These delays vary for different sensory modalities (e.g longer for hearing than for proprioception), but are around 100 milliseconds. Therefore, we effectively live in the past, with the control systems only having access to outdated information about the external state of the environment and internal state of the body [1].

1.1.3 Uncertainty

Uncertainty refers to the incomplete knowledge either with regard to the state of the environment or of the task or rewards one could receive. Among noise and delays, there are many other sources of uncertainty; for example, uncertainty can be caused by limitations in receptor density and the representation of an analog world with the digital neural code [1]. The inherent ambiguity in sensory processing is also a source for uncertainty; for instance when a three-dimensional world is projected onto the two-dimensional retina [9].

When reflecting on all that problems one might wonder how humans are not total helpless in day to day life or how it is even possible to perform motor tasks at a high level. Therefore humans can apply several mechanisms to overcome the described difficulties.

2 Multisensory Integration

Multisensory integration helps us to deal with uncertainty and noise. Distinct sensory modalities can represent the same information about the state of our body or the state of the external world (e.g., auditory and visual location of a noise source). When these different modalities are experimentally put in conflict, for example by mismatching the vision and sound of a human speaking, the percept is something intermediate between the percept of each input alone [10]. Even for normal sensory inputs, our sensory system is variable and can have biases. Because of that, the estimates from distinct modalities are not likely to be equal. Within the Bayesian framework, we can ask what is the most likely state of the world which showed the multiple sensory inputs. Such a Bayesian model predicts that a scalar estimate from two different modalities, such as the visual and haptic size of a held object, should be weighted and averaged to calculate an optimal estimate. Most importantly, the weighting of each modality should depend on its reliability, with the more reliable stimuli contributing more to the final estimate. This kind of model is supported by experimental studies of size estimation from visual and haptic cues [11], location from visual and auditory cues [12], and has been suggested to explain ventriloquism [13]. The study by Ernst and Banks will be explained in the following.

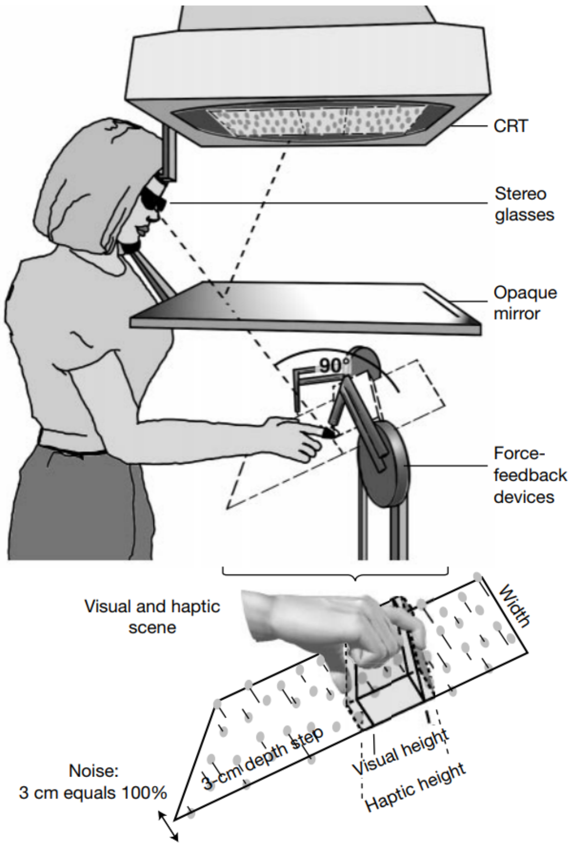

Fig. 1: Experimental Setup: a, "Observers viewed the refection of the visual stimulus, presented on a cathode ray tube (CRT) binocularly in a mirror. The haptic stimulus was presented with two PHANToM force-feedback devices, one each for the index finger and thumb" [11].

2.1 Visual Haptic Integration

In order to examine how examine if humans combine two sensory stimuli weighted by the reliability of the stimulus Ernst and Banks manipulated put the visual and haptic size of an object into conflict. Subjects were presented two objects: one comparison object which had always the same size (50 mm optic and visual) another object where the visual size and haptic size differed by -6 to +6 mm. The subjects had to chose which object was taller. In order to examine the weighting of the two stimuli different levels of noise were added to the visual stimulus.

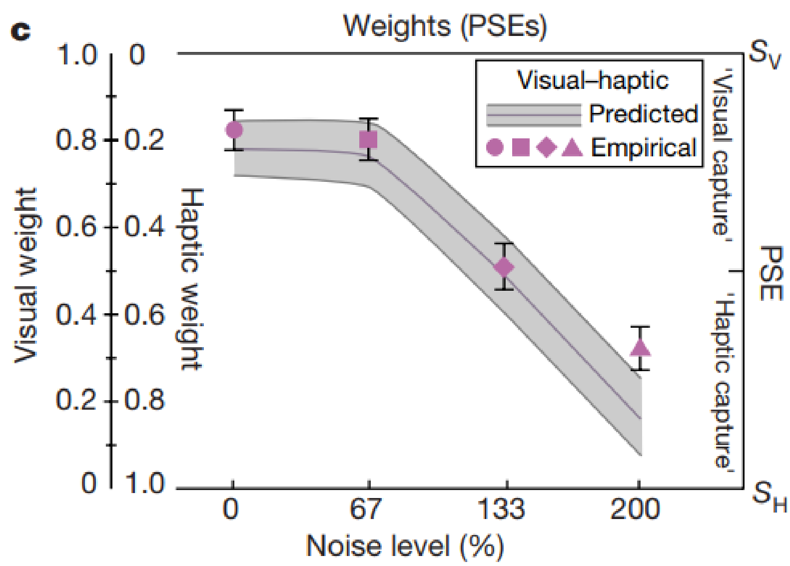

Fig. 2: "Weights and PSEs. Abscissa represents the noise level, left ordinate represents visual weight (wV; haptic weight is 1 - wV) and right ordinate represents the PSEs relative to S V and S H. Purple symbols represent observed visual weights obtained from regression analysis of PSEs (equation 6) across D. Shaded area represents predicted weights expected from within-modality discrimination (a; equation (5)); its height represents predicted errors given the standard errors of the within-modality discrimination" [11].

2.1.1 Conclusion Study

The more noise was added on the visual signal the more weight was given to the haptic size of the object. The weights of the stimuli were approximately mathematical optimal.This means using maximum likelihood estimation This is an estimation where the weights W of two stimuli X_{visual} and X_{haptic}, are calculated according to their variance σ^2: $\Theta = W \cdot X_{visual} + (1\text{-}W) \cdot X_{haptic}$ with $W = \sigma^2_{haptic} / (\sigma^2_{haptic} + \sigma^2_{visual})$

3 Forward Models

While multisensory integration deals mainly with uncertainty forward models help to deal with delays (in addition to noise) [1]. A forward model creates an instance of the motoric and sensoric system of the body. By doing so it works as a neural simulator that predicts the effects of motor commands [1]. The concept of are forward model is difficult to validate experimentally. This is due to the fact that the output of the forward model is a prediction of a future state which is not measurable, but used to adjust motor commands [14]. However there are several studies supporting that estimations of the state of the body are made by sensory feedback as well as a forward model [15] [16]. These studies used saccades (rapid eye movements between two points) to examine the existence of forward models Subjects had to perform limb reaching movements and simultaneously track their limb position with their eyes. Thereby a it was found, that the saccades moved to a position 196 ms in advance of the limb position [15] . When disturbing the arm position it could be shown that saccades were initially suppressed for 100 ms after the disturbance. After the disturbance a recalculation followed and the eyes moved to a predicted position 150 ms before the hand. This suggest that the model has access to an efferent copy. The recalculation however was incorrect when the perturbation also changed the environment (for example by adding a resistive field). So subjects could not correctly predict their future limb position. This leads to the conclusion that sensory feedback and a model of the external world is used to predict a future outcome. When the model of the external world was wrong, the prediction was also not correct. In cases were there was time to learn the changes in the environment the model eventually performed correct predictions again [16] .

Prediction can be used for perception as well as for estimating the state of the body. More precise, sensory prediction can be done by predicting the state of the body and using this sensory prediction to cancel out the sensory effects of movements (re-afference) [1]. This cancellation of self-generated sensory feedback can be implemented to enhance the detection of sensory information that comes from the external world [17].

Another piece of evidence for this theory is that tickling yourself is way less ticklish than externally generated tickle. I order to distinguish between the self-generated movement to perform the tickle and the tactile sensation on the skin robotic manipulation was used. This was done by adding short delays or small changes to the movement. After manipulating the self generated tickle, the sensation became more ticklish [18]. This shows that the prediction of our system which are used in sensory perception are highly exact temporally and spatially. A similar effect could be shown in force generation. Self-generated forces are perceived weaker than externally-generated forces.[1]. Additionally, the idea of an efference copy that predicts the sensory input of a movement and removes the this prediction from the sensory perception is supported by the study of self-generated head movements. Thereby the predicted cancellation signal is subtracted but the vestibular nuclei [19][20] .

4 Outlook

Since this paper only contemplated a few selected mechanisms other principles should be shortly mentioned as well should be thought about possible applications of those computational mechanisms. A very powerful strategy is learning. Learning deals with non-linearity, non-stationarity and delays. Optimal control theory is also worth mentioning, since it is the only strategy that deals with

redundancy. This is done by optimizing the costs of a movement[1]. Costs can be anything from the loss of a desired position to energetic costs [1].
Although the material presented in this paper is mostly basic research, one could think about applications in robotics. The application could be especially interesting, because the computational principles used by humans could be implemented easier than other neurobionic ideas.

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