ENGLISH SUMMARY
HUMAN MODELS OF THE WORLD

Humans make predictions about the timing of events everyday, whether they involve the speed of oncoming traffic, the time taken for a tennis ball to reach a racquet, or the time a broth takes to boil. There are often at least two sources of information available to humans while making timing predictions in such tasks, visual observations and prior experience. In this thesis, we contribute to the study of the computational basis for how humans combine visual information with their experience, and learn statistical regularities in the world that make predictions more accurate and precise over time. For example, despite having truly deplorable eyesight, if you forgot your glasses at home and attempted to cross the street in front of your house, your general experience about how fast cars move in your neighborhood would provide you with more reliable information than the blurry images before you. In this thesis, we study how sources of information are utilized in order to make reliable predictions about the world.

One of the sources of information crucial to making predictions is our prior experience with variables in the world. We therefore begin this thesis by looking at how our predictions are influenced by unexpected changes in the time course of a variable that we have become familiar with. For example, in the sport of cricket, after several sessions of fast bowling pitches, fielding captains often introduce a spin bowler to perplex the opponent batsman. This seems like a clever strategy because batsmen become accustomed to the statistics of the fast bowling and tune their predictions to match its parameters. When a sudden switch is made to spin bowling, batsmen are often caught on the wrong foot and make errors in predicting the trajectory or timing of the ball. From a theoretical point of view if we could make one recommendation to the batsman it would be to reduce their reliance on experience and increase their reliance on fresh observations of ball-speed from the spin bowler. In engineering terms, this action would be equivalent to 'increasing the gain' of the batsman's prediction system. In Chapter 2, we study whether humans are able to increase or decrease their gain as the statistical nature of the observations in the world change. We find that not only are
humans able to adapt to systematic changes, we provide evidence that they alter their gains while doing so.

In Chapter 3, we take a closer look at human predictions in environments with different properties. A statistical environment can be correlated over time, for example a stockmarket index is correlated over time because each day's value is obtained by adding random noise to the previous day's value. On the other hand, if you are looking at the odometer in your car while trying to maintain 130 km/h on the Dutch highway (where possible), you will find that on average the red needle will be on 130 but will sometimes overshoot and sometimes undershoot at random. This is an example of an uncorrelated distribution that randomly fluctuates around a mean value. While making predictions in these two very different types of environments, correlated (stockmarket) and uncorrelated (odometer), humans seem to be using the same strategy, which is strange because in order to be accurate one requires different strategies for each of these two environments. Why humans predictions betray the belief that uncorrelated distributions contain some correlation has been a long-standing puzzle in economics, psychology, and forecasting. In general, humans seem reluctant to embrace the concept of randomness. For example, a gambling addict may falsely believe that losing ten hands in a row will somehow increase their chances of winning the next, which is a misguided belief since in terms of pure mathematics each throw of dice is unbiased, independent and equi-probable. In Chapter 3, we provide a theoretical and computational model for the basis of such behavior. We demonstrate how crude online approximations of the parameters needed to make predictions, may result in human biases in uncorrelated environments.

Sometimes matters in the real world are complicated further because we have to estimate one variable with respect to another. Here it becomes crucial that the relationship between the observed variable and the predicted variable is fully understood. For example, the higher a tennis ball is played in the plane of one's body, the lower its trajectory will be. Therefore, if one's goal is to clear the net from the baseline, the ball should be struck from below whereas to make a successful volley at the
net, the ball should be played from above to ensure its immediate descent. This is a simple inverse linear mapping, however, on many occasions these relationships can be more complicated. Recognizing the true relationship between variables helps us make reliable predictions. In the Chapters 4 and 5 of this thesis, we study two facets of this problem 1) how humans learn these relationships and 2) how the rates of learning relationships in the world are influenced by the complexity of the relationship itself.

In Chapter 4, we study how the statistics of presentation influence how relationships between two variables are learned. Most tennis coaches believe that beginners should be gradually trained. They expose the trainee to basic strokes and gradually ramp up the technical requirements for the stroke. Although we do not have direct evidence for the sports domain, recent work in human sensorimotor learning would advise the use of a different approach. Our findings in Chapter 4 (and recently those others) suggest that learning is facilitated by random presentation, i.e., based on our results, it seems that learning is more efficient and faster when training spells randomly contain different speeds of spin, reverse-spin, flat strokes, and volleys. We find an interesting paradox in our experimental data. We find that when presented with correlated information, humans perform accurately but fail to learn the global properties of the learning problem. This situation is analogous to driving on a dark road with some part of the road lit up with headlights. You will be able to find your way to your destination, but may never know how much the road curved in the last hour or two. Therefore, you have performed the task of driving through a very local experience of the road, however, it can be very hard to integrate these local elements over time to gauge the global properties of the road. We conclude that accuracy sometimes comes at the cost of global perspective, and making errors therefore has certain tacit benefits.

In Chapter 5, we try to determine how humans learn relationships among variables in the world. We call these learned states human world models. We investigated whether human world models accurately reflect the true model presented to them or are they mere approximations. The
possibilities are manifold. Humans could behave as existing computer algorithms do and break down complex problems into a series of smaller problems. On the other hand humans could develop a sense of global functions that can generalize to many different observations. In Chapter 5 we test many different types of models and heuristics to determine which explains human performance best. Given the set of hypotheses that we tested, we found it highly likely that humans mostly grasp the true nature of the functions provided to them rather than use approximations.

We also investigate the role of model complexity on model learning. We examine how the rates of acquisition of various models differ based on the complexity of the model. It was the fourteenth century English Franciscan friar William of Ockham who first propounded the idea that when considering different models with equal ability, the simplest among them should be chosen (Ockham's Razor). The question arises whether the human brain uses the simplest hypothesis that can reasonably explain a dataset, or does it by default start with a complex model that can explain many different datasets. In Chapter 5, we find evidence to suggest that the human brain is quicker to select a simple world model for a simple dataset in comparison to selecting a more complex world model for a more complex dataset. This effect is systematic and shows a preferential bias in the selection of simpler models.

In summary, in this thesis we provide new perspectives on a few open problems in the field. We find evidence that human prediction processes make the use of dynamic parameters. Further, we propose that human biases in various statistical environments can be explained by the shortcomings incurred during online estimation processes of such environments. We develop a new computational principle to demonstrate how this may occur. We then look at the interaction between serial correlation and correlation among variables. We find that the existence of serial correlation hinders the learning of relationships among variables. We also determine whether human models of the world are accurately represented. We find that this is the case for the hypotheses set that we tested. We determine that humans exhibit a bias towards simpler models.
as evidenced by the rates of acquisition of models of different complexities. In conclusion, the accuracy of human world models depends upon the nature of how the observations are sampled. When sampled independently, world models are often veridical and more agile than previously believed.