# Sequential effects in prediction

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**Abstract**

We studied a simple binary prediction task and discovered that, when making predictions, humans display sequential effects similar to those in reaction time. Moreover, we found that there are considerable individual differences in sequential effects in prediction, again similarly to reaction time studies. We discuss our results in light of the view that sequential effects are the trace of an attempt at detecting a pattern in the sequence, as well as the possible influence of randomness perception in our results. We conclude that the same pattern detection mechanism is likely to underlie sequential effects in reaction time and prediction.

**Keywords:** sequential effects; prediction

When responding to a sequence of stimuli, human performance depends on the past sequence of stimuli, often to a larger extent than on the properties of the stimuli (e.g. Bertelson, 1961; Cho et al., 2002). This phenomenon, known as 'sequential effects', is commonly interpreted as the product of an attempt at detecting a pattern in the sequence of trials, and in particular whether it is a repeating or alternating sequence. Take for instance a random sequence with two possible elements: after a repeating run, people tend develop an expectation that the next event will be the same; similarly, after an alternating run, an expectation will develop that the next event will alternate relative to the last one. This is reflected in human reaction times (RTs) which tend to be faster for those events which are expected and shorter for those that are not. For instance, let 'R' and 'A' stand for repetitions and alternations of stimuli: after seeing RRRR people react faster if the next event was R, and slower if it was A; conversely, after seeing AAAA they will react faster to another A and slower to an R. If we plot mean RT for all possible histories of events we obtain a 'profile' of sequential effects. Figure 1 shows a commonly obtained profile of sequential effects, often referred to as 'cost-benefit' in order to highlight the trade-off in RT after a given sequence.

But what if, instead of reacting to each element, a prediction must be made about what the next one will be? It follows from the expectation-based account expounded above that those events which are expected should be predicted the most (i.e,. prediction frequency should be *negatively proportional* to RT). However, the longer a repeating run is, the more people have been found to predict that the sequence will alternate (Jarvik, 1951), an effect known as the 'gambler's fallacy' (Oskarsson, Van Boven, McClelland, & Hastie, 2009). At first sight, results from prediction experiments where the gambler's fallacy is observed are incompatible with those of RT experiments - where it is found that RT decreases as a function of run length (Bertelson, 1961) - since, together, the findings from the two paradigms paradoxically imply that humans predict more and more that which they predict less and less. Also, note that, since people react faster when a pattern is confirmed, they are going *with* the pattern - i.e. behaving as if the pattern will continue - whereas, when predicting, they seem to be going *against* the perceived pattern.

One possible explanation for the differences observed between prediction and RT is that people might perceive the sequence to be random in some cases and not random in others (Nickerson, 2002). It stands to reason that if a sequence is random, then any regular pattern encontered must be short-lived; if, on the other hand, a sequence is judged to be structured, then a pattern might be more likely to continue. Differences in randomness perception might influence results, but there is evidence that both phenomena - decreasing RT and increasing proportion of prediction with increase in run length - occur simultaneously, as both have been observed in experiments where subjects were made to predict - as well as react to - each stimulus (Hale, 1967; Perruchet, 1985). At first sight, this finding does not seem compatible with the randomness perception account, since that account would suggest that whether or not the sequence is percieved as random changes within the same trial. Thus, while randomness perception cannot be ruled out as a possible explanation for some results, it is not the full story.

Before a decision can be made to go with or against a pattern, the pattern must be detected in the first place. Parsimony suggests that the pattern detection mechanism underlying sequential effects in both prediction and reaction is the same, but that the information it conveys is being used in different ways, and this forms our first hypothesis. As evidence for this hypothesis, we will take any similarities in the profiles of sequential effects in prediction and reaction time. For instance, should the proportion of times people predict the next event to repeat or alternate (i.e., the prediction probability) be found to resemble the cost-benefit pattern in Figure 1, this would be taken as evidence that the same type of sequential effects can be found in RT and prediction. However, we do not know beforehand whether humans are going with or against the pattern in the sequence when making predictions. If going against the pattern we would expect prediction probability to be proportional to RT, and negatively proportional if going with the pattern. In the latter case the profile of sequential effects in prediction would look like an inverted copy of its RT counterpart (see Figure 1, right panel). Previous evidence points to the fact that humans are going against the pattern

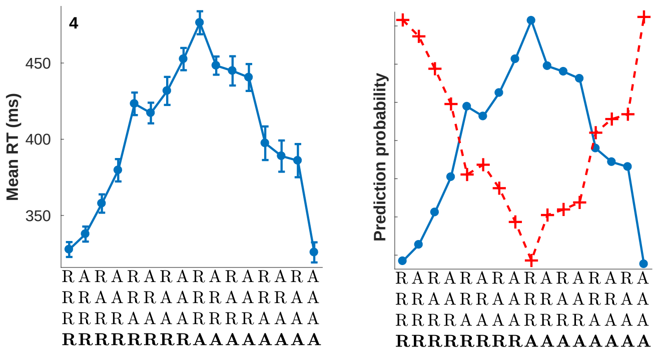


Figure 1: Illustration of working hypotheses. Sequences at the bottom are shown in terms of repetitions (R) and alternations (A) of stimuli and should be read from top to bottom with the last event in bold. Left panel shows reaction time data of a single individual included in the analyses performed by Gökaydin et al. (2016), illustrating the ideal profile of sequential effects, also known as 'cost-benefit'. Right panel illustrates what would be expected if prediction also displayed sequential effects similar to those observed in RT. The solid line on the right panel shows what would be expected if humans were going against the pattern in a prediction task, i.e. predicting more often that the pattern will continue; the dashed line shows what would be expected if subjects were going with the pattern.

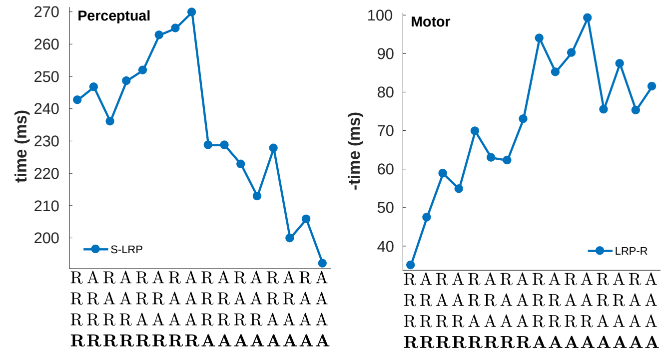


Figure 2: Perceptual and motor sequential effects. Both panels show data collected by Jentzsch and Sommer (2002). Left panel shows the evidence for a perceptual component of sequential effects (S-LRP) and the right panel for a motor component (LRP-R). See main text for an explanation of the meaning of these two components.

when predicting, so our second hypothesis is that prediction probability will be proportional to RT, and that the respective profile of sequential effects will show the same 'polarity' as that of RT (Jarvik, 1951; Hale, 1967; Perruchet, 1985).

## The structure of sequential effects

In order to test our hypotheses we must assess whether sequential effects in reaction and prediction are the same. However, this is not a simple matter of comparing results of two sets of subjects performing a reaction and a prediction task, as it is well known from reaction time studies that there is extensive variation in the profile of sequential effects depending on experimental parameters such as the interval between the stimuli (Soetens, Boer, & Hueting, 1985; Gökaydin et al., 2016), as well as for different individuals performing the same experiment. In fact, the 'typical' profile of sequential effects shown in Figure 2 (left panel) is the exception rather than the rule (Gökaydin et al., 2016). Therefore, in order to demonstrate that sequential effects in prediction are the same as those in reaction time we will try to show they have the same *structure*.

There is growing evidence that sequential effects in reaction time can be explained in terms of two separate components, one perceptual and related to the sequence of stimuli and the other motor in origin and related to the sequence of responses (Jentzsch & Sommer, 2002; Maloney, Dal Martello, Sahm, & Spillmann, 2005; Wilder, Jones, Ahmed, Curran, & Mozer, 2013; Gökaydin et al., 2016). Crucially, the relative contributions of the two components of sequential effects are known, and take the form of the profiles shown in Figure 2. Moreover, sequential effects in reaction time - across different participant and experimental conditions - are known to be well approximated by a linear combination of the two components, giving us a simplified working model of sequential effects in reaction time. Applying this model to results from a prediction task gives us a way of testing whether sequential effects in reaction time and prediction are similar.

Figure 2 shows the best evidence available about the two components of sequential effects, from an EEG study conducted by by Jentzsch and Sommer (2002). The authors measured the time between stimulus onset and the occurrence of the lateralised readiness potential (LRP), termed S-LRP; and the time between the LRP and the moment a response occurred, or LRP-R. Since the LRP is thought to separate temporally pre-motor from motor processing, S-LRP and LRP-R are considered to give a measure of pre-motor and motor processing respectively. By measuring both S-LRP and LRP-R as a function of the sequence of stimuli, Jentzsch and Sommer (2002) sought to capture the pre-motor and motor contributions towards sequential effects (see Figure 2). Further evidence from other studies shows that what Jentzsch et al. referred to as pre-motor processing can safely be assumed to be perceptual in nature and associated with the processing of stimuli (Maloney et al., 2005; Wilder et al., 2013). For this reason, we will refer to the two components of sequential effects simply as perceptual and motor, denoting them, respectively, as $P$ and $M$.

## Different ways of looking at the data

Sequential effects are usually studied in the context of two-alternative forced-choice tasks (2AFCs) where one has to react to each stimulus as quickly as possible (e.g., pressing one button if the stimulus appears on the left and another if the stimulus appears on the right). Error rates in this type of task tend to be quite low, which means that the sequences of stimuli and responses are very similar and that organising results as a function of one or the other yields the same results. By contrast, in a prediction task with two equiprobable stimuli, the error rate is 50% by design, and this means that the sequence of responses and of stimuli become uncoupled. This raises the question: should the sequence of stimuli or that of predictions be used in order to study the way in which predictions depend on the sequence? And what information is each type of analysis conveying? One possibility is that analysing predictions as a function of the history of predictions - which involve a motor action - we will recover the motor component of sequential effects in prediction; conversely, predictions as a function of the history of stimuli might yield the perceptual component.

## Method

### Participants

21 subjects (11 female, 10 male) participated in the experiment. Subjects were recruited using Amazons Mechanical Turk (Mturk) system. Only participants with at least 500 HITS completed on Mturk and with an approval rate of 95% or above were accepted and paid $5 USD for taking part in the experiment.

### Stimuli

Stimuli consisted of two white dots of radius equal to 30 pixels, horizontally separated by a distance in pixels equal to 20% of the width of the screen. The dots were white and displayed against a grey (RGB 0.5/0.5/0.5) background. During each trial, the two possible positions of the dots were indicated by two black squares equal in width to the diameter of the dots.

### Procedure

Each trial began with a 2000ms-long text display above the two black squares: 'Is the next dot on the left or on the right?'. Predictions were made with the 'f' key for 'left' and 'j' for 'right'. If a prediction was made during the 2000ms period, the corresponding black square's border would thicken and further key presses had no effect. Once 2000ms elapsed, the next dot appeared for 600ms, together with feedback (green tick for a correct prediction or a red cross for incorrect). If no prediction was made, a warning message 'Don't forget to guess' was displayed before the appearance of the next dot. If no prediction was made for five consecutive trials, the experiment stopped, and the message 'Please remember to respond' was displayed until the space bar was pressed. Each subject performed 500 trials separated into five blocks of 100 each, with an additional 10 practice trials. The sequence of dots was random, with the constraint that the frequency of left and right dots was equal for each block.

### Data analysis

In the sequential effects literature it has been customary to show results as an average of a few participants. However, recent work has uncovered that individual differences are not only substantial but also meaningful in that they reflect different contributions - perceptual and motor - towards sequential effects (Gökaydin et al., 2016). Thus, average results are not conclusive with respect to demonstrating that sequential effects in prediction are similar to those in reaction time.

In order to calculate the probability of repeating/alternating as a function of the history of stimuli for each participant, each participant's trials were separated according to five-long histories of predictions, with prediction probabilities being calculated simply as the relative frequency with which a repetition or alternation was predicted as the fifth event in each of the 16 possible five-event-long histories presented on the $x$-axis of Figure 1. For instance, denoting frequency by $f(.)$, the probability of alternating after predicting ARA was calculated as $p(ARAA) = f(ARAA)/(f(ARAA) + f(ARAR))$.

We will use $X_s, Y_s$ to denote the left/right dots and $X_p, Y_p$ the left/right predictions. In order to calculate the probability of repeating/alternating as a function of the history of stimuli, sequences such as $ARAR$ consisted of $X_sY_sY_sX_sX_p$ and $Y_sX_sX_sY_sY_p$. Probabilities of repeating/alternating were then calculated as above.

As discussed above, in order to assess whether sequential effects in prediction are similar to those in reaction time, we will use a simple model which is known to provide a good description of sequential effects in reaction time and apply it to sequential effects in prediction. Our model will consist of a simple linear combination of the perceptual elements of sequential effects. Our model then reads as $aP + bM$, where $a$ and $b$ are scalar free parameters and $P$ and $M$ are the perceptual and motor components of sequential effects - effectively just the profiles shown in Figure 2.

## Results

We will look primarily at individual results given that we know from reaction time studies that individual differences can be substantial (Gökaydin et al., 2016). Moreover, as discussed above, looking at averaged results is inconclusive with respect to assessing whether prediction and reaction time show the same type of sequential effects. We will discuss two types of analysis: prediction probability as a function of the history of predictions - prediction history profiles for short - and prediction probability as a function of the history of stimuli - or stimulus history profiles. Results from both types of analysis will be shown in turn. Overall, prediction history profiles emerged as having a larger number of individuals with a better fit to the combination of the components model: 17/21 prediction history profiles had an $R^2$ greater than 0.5, compared to 8/21 for stimulus history profiles. Note that a clear profile of sequential effects on one type of analysis was no guarantee that a clear profile emerged for the other type: several subjects displayed clear sequential effects on their prediction history profile but not in their stimulus history profile; conversely, one subject displayed strong sequential effects on the stimulus history profile but not on

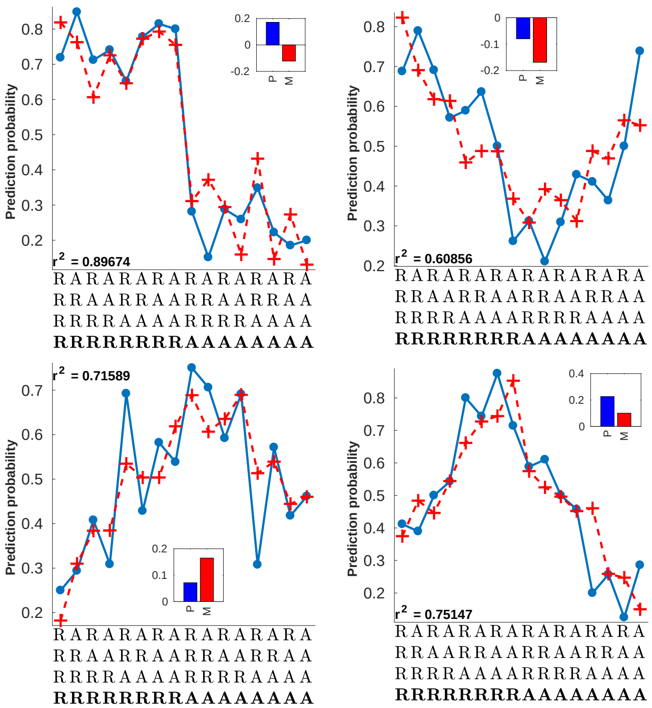


Figure 3: Individual sequential effects in prediction as a function of prediction history. Blue solid lines- empirical mean prediction probability. Red dashed lines - best fitting linear combination of the form $aP+bM$ where $P$ is represented by S-LRP and $M$ is represented by LRP-R. Inset bar plots show coefficients $a$ ($P$) and $b$ ($M$). Also shown is the $R^2$ value of the fits.

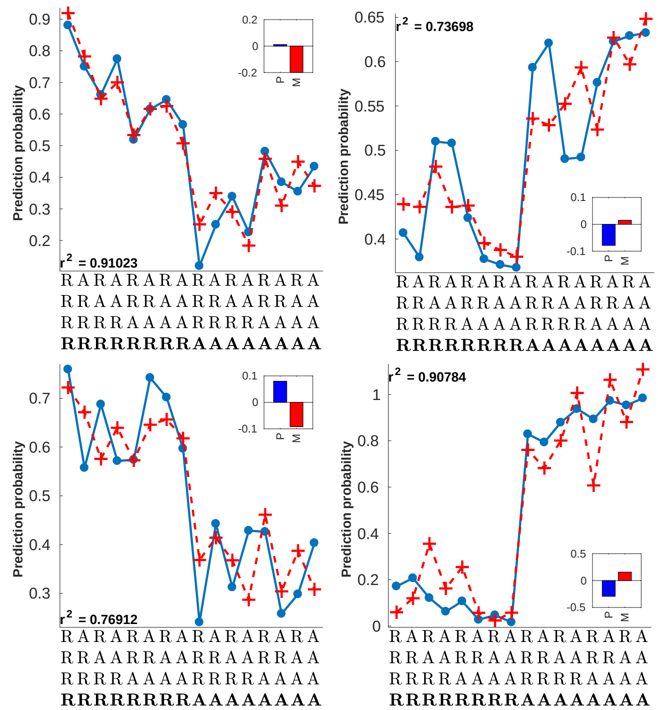


Figure 4: Individual sequential effects in prediction as a function of stimulus history. Blue solid lines- empirical mean prediction probability. Red dashed lines - best fitting linear combination of the form $aP+bM$ where $P$ is represented by S-LRP and $M$ is represented by LRP-R. Inset bar plots show coefficients $a$ ($P$) and $b$ ($M$). Also shown is the $R^2$ value of the fits.

the prediction profile.

Figure 3 shows a sample of prediction history profiles from individual participants - chosen on the basis of their goodness of fit to the model, as well as being representative of different types of profile. The lower-right panel of Figure 3 shows a typical cost-benefit profile, the hallmark of sequential effects in RT, observed here for the first time in prediction. The lower-left panel shows yet another commonly observed type of sequential effects, the result of a stronger motor contribution. The top-left panel shows an example of an approximately 'two-tiered' profile, the product of a positive perceptual and negative motor coefficient. Finally, the top-right panel shows an individual with a negative score on both components.

Figure 4 shows a selection of individual stimulus hostory profiles, again chosen on the basis of their good fit and because they illustrate previously known profiles from RT studies. The profile on the top-left corner of Figure 4 is of particular relevance: not only did it occur in several subjects (4) but it consists of an 'inverted' copy of what is thought to be the motor element of sequential effects. The top-right corner of Figure 4 shows a profile that is best fit by the perceptual component of sequential effects in isolation, raising the possibility that it too can also occur 'inverted' and in isolation. The remaining profiles in Figure 4 (bottom two) show two profiles which are consistent with a mixture of the two components of sequential effects, where the motor component is inverted but not the perceptual, and vice-versa. These types of profile, resembling an almost two-tiered dependence on the last event and whether this was a repetition or an alternation, are common at the individual level in RT studies despite only recently having been described (Gökaydin et al., 2016). Interestingly, no single participant exhibited a good fit to a combination of the two components where both had positive coefficients. Note that the two sets of subjects shown in figures 4 and 3 are different, with the exception of the lower-left panel of both figures, which show both types of analysis for the same individual.

Recall that, based on previous results, we hypothesized that prediction probability would be proportional to reaction time, reflecting the fact that humans predict less that to which they respond the fastest, and vice-versa. In the context of our model, this would imply that the coefficients of perceptual and motor components have the same sign on average in reaction time and prediction. Figure 5 shows the coefficient values of both components for all the individuals with very good fit to the model ($R^2 > 0.7$). At first sight our re-

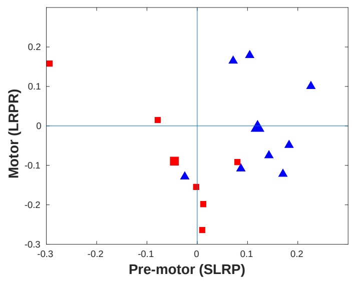


Figure 5: Coefficients of the best fitting linear combination $aP + bM$ for those subjects with $R^2 \geq 0.7$. Blue triangles show the coefficients of the fit to results as a function of prediction history; red squares show fits to results as a function of stimulus history. The large blue triangle and red square show the respective means.

sults differ from RT experiments in one respect: in prediction profiles at least, the motor component often varies from a strongly positive to a strongly negative sign, whereas in RT it has almost always a positive sign (see Gökaydin et al. (2016), supplementary information). With respect to differences between prediction history profiles and stimulus history profiles - squares and triangles in Figure 5 - there is a hint that perhaps stimulus history shows one or the other component in isolation, whereas prediction history shows a more balanced mixture of the two components, but it is too early to draw any firm conclusions.

## Discussion

Our first hypothesis posited that we would find sequential effects in prediction similar to those in reaction time. The evidence presented here - while falling short of demonstrating that sequential effects in reaction and prediction are the same - does strongly suggest that sequential effects in prediction are similar to those in RT insofar as they are well captured by a combination of the two components of sequential effects in reaction time - perceptual and motor. That such clear profiles of sequential effects were obtained (Figures 3 and 4) was somewhat surprising given the smaller number of trials relative to typical RT tasks, as well as the less constrained nature of the task. Still, results were visibly noisier when compared to reaction time experiments, and many subjects failed to exhibit any appreciable fit to the two-component model. Nevertheless, we cannot rule out that those individuals who did not exhibit a good fit to the model exhibit a new type of sequential effect which is meaningful. In order to firmly establish the nature of sequential effects in prediction an experiment with larger numbers, followed by latent variable analysis - such as principal components analysis (PCA) (Gökaydin et al., 2016) - is necessary. This would allow us to match the structures of sequential effects in prediction and reaction time, rather than just a few individual results.

We also hypothesized that prediction probability would be directly proportional to RT, rather than negatively proportional as is more intuitive. Again in this case conclusions can only be drawn on average, since there is considerable variation in the sign of the two components in both RT (see Gökaydin et al. (2016)) and prediction (Figure 5). Despite the small sample size, one difference did emerge: the sign of the motor component in prediction profiles ranges from strongly negative to strongly positive, whereas in RT studies the motor component seems constrained to be positive. Another interesting observation is that the motor component with a negative sign and in relative isolation - i.e. not in combination with the perceptual component - occurred in half (4/8) of the stimulus profiles with an $R^2$ greater than 0.5. In other words, when analysing results as a function of the history of stimuli, half of the participants were using only the motor component of sequential effects. Moreover, when analysing results as a function of the history of predictions, we obtained clear contributions from both the motor and perceptual components. At first sight, these results at odds with the interpretation of the components of sequential effects as associated with the perceptual and motor systems since - in a task where the sequence of responses and stimuli are de-coupled - we should recover the motor component when looking at the sequence of responses and the perceptual component when looking at the sequence of stimuli. Therefore, our results may force a re-interpretation of the motor/perceptual association of the two components of sequential effects.

There is some debate regarding the computational nature of sequential effects. Some authors argue that sequential effects reflect the tracking different types of statistics in the environment (Wilder, Jones, & Mozer, 2009), whereas others argue that sequential effects are instead the product of the separate detection of alternating and repeating patterns (Maloney et al., 2005). We will use the latter interpretation in order to guide our discussion, but the different explanations are not incompatible and the ensuing discussion would hold if we interpret sequential effects as tracking different statistics. In the context of the pattern-detection interpretation, the perceptual component is the natural candidate for an alternation detector, whereas the motor component would play the role of a repetition detector (see (Gökaydin et al., 2016) for an explanation of this mapping). A change in sign of either coefficient would therefore imply a change in whether a particular subject is going for or against the respective pattern. For instance, when predicting, a positive sign of the motor component would mean that the the participant is going against a perceived repeating pattern, and the opposite is true for a negative coefficient.[1] In light of this, we can now see that the variation in the sign of the coefficients of both components of sequential effects (Figure 5) may reflect a differential treatment of repeating and alternating patterns: in some cases subjects are going against both types of pattern - repeating or alternating - and other times against one but with the

[1]Note that in RT this is the opposite: a positive sign means going with the pattern, and negative against it.

other. The only combination we did not obtain was a negative sign on both coefficients, which would imply going with both patterns.

Earlier we proposed that the subjective perception of randomness might influence the polarity of sequential effects, since whether or not a pattern will continue depends on whether the sequence is random or not. At first sight, the randomness perception account would seem to imply that humans either go against both types of pattern - repeating and alternating - or with both. After all, if we perceive the sequence as being random we should bet against both repeating and alternating sequences continuing, and the opposite if we believe the sequence to be structured. However, it is conceivable that the perception of randomness has a differential effect on repeating and alternating patterns or, somewhat equivalently, that individuals give different weight to repetitions and alternations when judging a sequence to be random. In fact, it is well known from RT studies that there are substantial individual differences with respect to sensitivity to repetitions and alternations (Soetens et al., 1985; Gökaydin et al., 2016). In our experiment we did not bias the participants either way, and it is therefore natural to assume that individual perception of the random nature of the sequence would vary depending on endogenous factors. One way to test the influence randomness perception on sequential effects in prediction would be to conduct the same experiment giving participants a strong hint that the sequence is random, and contrasting these results with a situation where it is implied that the sequence has a pattern.

Some of the participants in our study exhibited a clear prediction history profile, some a clear stimulus history profile, and some both. The implication is that some humans are tracking the sequence of predictions, others the sequence of stimuli, and others both, in order to try and make predictions. What is it that makes some people more sensitive to one or the other type of information? The perception of randomness may yet again play a role in this respect, since a belief that the sequence is random should lead to a dismissal of the sequence of stimuli as uninformative. If participants believe the sequence is random they might try to generate the most random possible sequence of responses by using their repetition and alternation detectors 'in reverse' in order to create a sequence of responses that is poor in repeating and alternating patterns. If this were the case, we should expect to see a positive coefficient on both components in those participants with a clear prediction history profile (blue triangles in Figure 5), which seems to be the case for a few subjects, but not all. Again, we cannot discard the possibility that individual differences in sensitivity to repetitions and alternations might play a role in this case, and that some individuals might put more or less emphasis on repetitions or alternations when generating the most random sequence possible.

## Conclusion

We have shown for the first time that prediction tasks display sequential effects similar in nature to those observed in reaction time. This work goes some way towards unifying the areas of prediction and reaction time in binary decision tasks.

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