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WAVE THEORY AND SIMPLE REACTION TIME

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Abstract

Simple and choice reaction paradigms are often used to illustrate that a concatenation of psychological processes leads to increases in response time. Simple response times require only the recognition of the occurrence of a stimulus, while the more complicated choice reaction task requires discrimination and/or recognition. We show that Wave Theory applied to the single response case of simple reaction time predicts well-known experimental phenomena. The difference between simple and choice RT results from the subject’s control of response thresholds. Thus, a single psychological process accounts for both simple and choice reaction time data.

Helmholtz, deJaager and Donders laid a solid foundation for the use of reaction time in the study of physio-psychological processes. Their common, fundamental assumption was that the more complex a discrimination the more processes needed for a reaction to occur. Complexity of processing must increase reaction time.

For example, deJaager (1865/1970) presented subjects with either a white or a red light and measured the time taken to respond. The average time was 188msec. When either light could occur, and a subject knew in advance which color would appear, the average reaction time was 184msec. When these same subjects did not know in advance which color would appear the average time to respond was 356msec. The difference in average response time, 356-184=172msec, led deJaager to conclude “that in a situation which involves making decisions, a considerable amount of time is needed in order to identify the stimuli and to react as required (1865/1970, p. 68).” We are left with the impression that simple reaction experiments lead to fast response times and that when the same stimuli require identification additional psychological processes tack on additional response time.

The conclusion seems clear, but the clarity is diminished somewhat by Cattell’s (1886) measurements of reaction time to the presentation of a light. As shown in Figure 1, Cattell discovered that response time decreased as the intensity of the light increased. The least intense light produced a mean reaction time of 308msec for Berger and 251msec for Cattell. The most intense yielded a mean response time of 168msec for Berger and 128msec for Cattell. The differences between maximum and minimum times, 140msec
for Berger and 123 msec for Cattell, are large enough to suggest that something other than the process of deciding to respond is involved.

The Cattell and Berger data challenged ideas about neural conduction: in particular, the idea that reaction time is the sum of response times for successive segments of the neural pathway starting at the sensory receptor and ending at the response effector. If this Neural Series Hypothesis is to be believed, how can we account for the large decline in response time as stimulus intensity increases? The neural pathway does not shrink. Nevertheless the results are not to be denied. When a choice between two stimuli is required response time increases. Response time also increases as stimulus intensity decreases.

Emerson (1970) argued that simple RT variability resulted from a process based on Brownian motion with a drift rate dependent upon signal strength. Other theorists, such as Hick (1952), argued that the subject must always make a choice. When only a single stimulus is presented, as in simple RT experiments, the subject’s choices are either to respond or not, while in choice RT experiments the subject must respond or not to a particular one of several stimuli. We extend Hick’s and Emerson’s ideas. First, there is no fundamental difference between simple RT and choice RT experiments. Second, the difference in experimental findings is due to the differing constraints placed on a single sequential decision mechanism.

The mechanism is described by the Wave Theory of discrimination (Link, 1992). The theory, an elaboration of earlier work by Link and Heath (1975) and Link (1975), postulates that when a stimulus is presented the experimental subject compares the waveform evoked by the stimulus to a standard, or referent, waveform by subtraction. Momentary values of this comparison are accumulated until a response threshold is first exceeded. Then a response occurs.

As Hick observed, the simple reaction experiment requires that the subject decide whether a change in ongoing sensory activity has occurred or is occurring. From this
perspective the standard or referent is the background activity during the periods when stimuli are not present. During these quiescent periods neural activity is the result of many ongoing activities that generate a variable baseline of neural quanta. Within a time epoch, $\Delta t$, the magnitude of the background is characterized by a Poisson distribution of neural amplitude. The Poisson distribution has only a single parameter $\lambda_0$ and has mean value equal to $\lambda_0$. The reaction stimulus produces a distribution of neural quanta with Poisson parameter $\lambda_1 > \lambda_0$. The accumulation of differences between these Poisson waveforms, between excitatory and inhibitory activity, must be accumulated until a response threshold is exceeded. Then the subject initiates a reaction response.

Major features of this decision process appear in Figure 2. On the abscissa are time epochs during which neural activity occurs. The successive differences between two Poisson waveforms are represented as bars extending above and below the value zero. For this illustration the mean values of the Poisson distributions are $\lambda_0 = 20$ and $\lambda_1 = 21$. The differences appear to vary only slightly around the value zero. However, the accumulation of such small differences grows quickly until the amount of accumulated difference first exceeds the response threshold at say $A=100$.

For comparison, and to illustrate an often overlooked feature of stochastic processes, two baseline Poisson waveforms are compared against each other. The accumulated difference remains positive over a large range of epochs, not reaching the response threshold at $A$ during any time epoch.

When only a single response is required, as in simple RT experiments, does only a single response threshold exist at $A$? A second response threshold at a value such as $B=-50$ may correspond to a decision to not respond. Although never directly observed, this non-response threshold may still play a large part in determining the subject’s performance.
The properties of the decision mechanism operating in the conditions of simple RT responses can be determined by analysis of the two-response case. Assume for the moment that a response threshold exists at position \(-B = -50\) in Figure 2. The probability that the comparison of the "reaction" stimulus to the background activity produces a stochastic path that reaches A before B is,

\[
P_A = \frac{e^{\theta B} - 1}{e^{\theta B} - e^{-\theta A}}
\]

where A and B are the response threshold values, and \(\theta = \ln(\lambda_1/\lambda_0)\).

The probability of reaching the response threshold at A depends on A, B and \(\theta\). Regardless of the magnitude of \(\theta\), as A approaches zero \(P_A\) approaches one. Also, as B increases the response threshold at B becomes increasingly negative and the response threshold approaches minus infinity. As B approaches infinity the two values of \(e^{\theta B}\) in Equation 1 increase and \(P_A\) again approaches one. One way or the other there must be a response to the "reaction" stimulus.

As this analysis shows, the response probability approaches one as A approaches zero, or as B approaches infinity. Of course, the value of B can not physically equal infinity nor can A equal zero. Both must be set at physically realizable values to keep the probability of responding when you should not, or not responding when you should, small.

The duration of the response to the "reaction" stimulus is the major focus of our analysis. In the case of two response thresholds the mean response time, the time taken to reach either response threshold, given a presentation of the "reaction" stimulus, is

\[
RT = \frac{1}{(\lambda_1 - \lambda_0)} \left[ P_A(A) + (1 - P_A)(-B) \right] c\Delta t + MT
\]

where \(MT\) is the component of response time not associated with the decision process and \(c\) is a constant of proportionality relating the values of \(\Delta t\) to the units of the experimenter's clock, usually milliseconds. Analysis of this equation shows that as B increases to infinity, \(P_A\) approaches one and the right hand term in brackets, \((1 - P_A)(-B)\), approaches zero. Consequently, for the conditions of simple reaction time, as the response threshold at B approaches minus infinity the simple RT approaches

\[
RT = \frac{A}{(\lambda_1 - \lambda_0)} c\Delta t + MT.
\]

Two features of this equation merit our attention. First, the value \(A\) is a characteristic of the subject, of how much accumulated information is required before a response will occur. The smaller the value of \(A\), the shorter the response time. Link (1992) showed how inducements to change the value of \(A\), such as the RT deadlines used by Link and Tindall (1971), generate changes in RT in agreement with the predictions of Wave Theory.
The second feature is the denominator, \((\lambda_1 - \lambda_0)\). Given that the background activity remains stochastically stable and \(A\) remains fixed, changes in RT are due to changes in the value of \(\lambda_1\). As stimulus intensity increases, \(\lambda_1\) increases and RT decreases. Such changes in RT were recorded by Cattell (1886), as shown in Figure 1, and are the topic of the companion paper by Bonnet and Link (1998). Moreover, Pins and Bonnet (1996) found RTs to depend on stimulus intensity in a similar way in either choice or simple RT experiments.

Both simple RT and choice RT are the consequence of the same decision mechanism. In simple RT experiments the subject can reduce the value of \(A\) to its minimum in preparation for the occurrence of the reaction stimulus. The response time is short. In choice RT experiments the subject must balance the values of \(A\) and \(B\) to limit the occurrence of errors. Compared to simple RT conditions the value of \(A\) in choice RT conditions must be increased in order to reduce the probability of false responses to the alternative stimulus. Ideally \(A\) and \(B\) are equal and large.

In simple reaction experiments anticipatory responses, False Alarms, may occur when the stochastic path generated by the comparison of the background activity with itself happens to reach the response threshold at \(A\). How many False Alarms might be generated? The probability of their occurrence is easily calculated. Under these "zero drift" conditions the limiting value of \(P_A\), as of \(\theta\) approaches zero, is the probability of a false reaction to background activity. This probability equals \(B/(A+B)\).

Paradoxically, as the value of \(B\) increases the probability of a false reaction increases. The reason more false reactions are not recorded during simple RT experiments is that the length of time for them to occur may be much longer than the interval between experimental trials. As shown in Figure 2, the stochastic path generated by a comparison of background activity with itself remains far below the response threshold of \(A = 100\). Nevertheless, False Alarms are a natural outcome of the stochastic process described by Wave Theory. For sufficiently small values of \(A\) False Alarms will occur frequently.

The sparse errors lead us to analyze response times as determined by the form of Equation (3). Changes in \(A\) and \((\lambda_1 - \lambda_0)\) cause the major changes to response time. Unlike the well-analyzed choice RT case, where errors help to confirm the predictions of Wave Theory, few errors are recorded in simple RT experiments. Furthermore, those that are recorded, the False Alarms, are those that occur before the next presentation of a stimulus. However, as illustrated in Figure 2, a quite long duration may be required before a False Alarm can occur. Thus, the often quick-paced trial structure of the experimental procedure may reduce the observable number of False Alarms.

The companion paper by Bonnet and Link (1998) presents a new method of analyzing RTs when such very low error rates occur, whether in simple or choice RT experiments. Another promising approach that deserves greater attention is that of Tichtchenko (1996) who computed the theoretical moments of the decision time component of simple RT given the Wave Theory assumptions. Mean RTs and variances, or standard deviations,
depend upon \((\lambda_1 - \lambda_0)\) and \(A\). Relations between these moments of the RT distributions can play an important role in verifying the Wave Theory interpretation of simple RT phenomena.

In summary, the response choice mechanism postulated by Wave Theory predicts phenomena observed in both simple and choice reaction experiments. Performance in simple reaction experiments depends mostly on the response threshold associated with responses to the “reaction” stimulus and the intensity of the stimulus. The response threshold at \(-B\), the threshold for not responding, can be large in order to reduce the occurrence of false positive responses and simultaneously limit the number of missed responses to the “reaction” stimulus. Because the probability of responding to the reaction stimulus is near one, the analysis of theory depends only on the analysis of response times. The companion paper (Bonnet and Link, 1998) creates a new method to investigate such results.

References


