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# THE ATTENTION THRESHOLD MODEL

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Selective attention theory (Sutherland 1959, 1964) accounts for many experimental psychologists' findings about discrimination learning (Mackintosh 1965); it has inspired a theory of the 'displacement activity' concept of the ethologists (McFarland 1966), and it seems to be proving useful in understanding the ecological idea of the 'searching image' (M. Dawkins, pers. comm.). In this paper it will be used to develop a more powerful version of a decision-making model, called the Choice Threshold model, which was proposed in a companion paper (Dawkins 1969). This new version will be called the Attention Threshold model. This paper will not be concerned with the process of learning; however a computer-simulated version of the model could easily be made to 'learn', and it seems probable that it might behave in a similar way to other formal attention models (Lovejoy 1965).

The earlier choice threshold model proposed a fluctuating variable, V, interacting with thresholds corresponding to external stimuli. A response, such as pecking in the chick, could be directed at a stimulus, say a red spot, only when V exceeded the threshold of that stimulus. When V was above more than one threshold simultaneously, both stimuli were equally likely to be chosen. This state of equality of choice probability was called 'suprathreshold indecision'. The attention threshold model was originally suggested as an explanation of its mechanism (Dawkins 1969).

A single ordering of thresholds was visualised, corresponding to all the stimuli at which the response could ever be directed, preferred stimuli of course having the lowest thresholds in the hierarchy. While it was recognized that stimuli must be evaluated according to many different qualities, colour, shape, size and so on, this was supposed to occur prior to the determination of threshold levels, in some unspecified 'heterogeneous summation' (Seitz 1940). The attention threshold model on the other hand specifies how interactions between cues come about, and is therefore able to make predictions in fields which were closed to the original model.

### Assumptions of the Attention Threshold Model

1. There is not merely one V/threshold system but many, one for each stimulus dimension or cue—colour, shape, size etc. Each one of these will be called simply a system. Each has its own variable V, and thresholds corresponding to a particular aspect, for example the colour, of stimuli. At any one instant the animal can *attend* to a maximum of one system, in the sense that at that instant the state of the V of that system and no other can have any influence on the behaviour.

2. The sequence of events potentially leading up to a choice begins by the animal *attending* to one of the systems at a particular *sampling instant* of time (Dawkins & Impekoven 1969). Subsequent events then depend on the state of V of that system at that instant. If V is above the threshold of only one available stimulus, that stimulus is chosen. If V is not above the threshold of any available stimulus no choice is made. In both these cases the animal is then free to initiate a new sequence by attending to the same or a different system. However if V is above 2 or more thresholds of available stimuli ('suprathreshold indecision') an *attention wave* is initiated.

3. An attention wave begins by the animal switching its attention to another system. The systems are arranged in a hierarchy such that attention can only switch from a higher to a lower one. This hierarchy is rigid in the short term, though it presumably could be modified by learning.

4. A system which is attended to as the result of an attention wave behaves as follows. If its V is above only one threshold, the corresponding stimulus is chosen, the attention wave comes to an end, and a new sequence can be initiated. Under all other conditions the attention wave proceeds to another system.

5. One of the systems, perhaps the lowest in the hierarchy, is called the casting vote system. It is unique in that if it is attended to a definite choice always occurs. It might plausibly be the system concerned with stimulus position, and an animal attending to it in a choice situation might simply choose the physically nearest stimulus. Thus a wave of attention, once initiated, must always end in a definite choice; if no choice

emerges from any of the other systems, it falls to the casting vote system to choose.

Some of these assumptions may seem arbitrarily complex. This is not really so; they were formulated in order to fulfil two conditions:

1. The attention threshold model should fulfil its original purpose of accounting for the 'suprathreshold indecision' of the original model.
2. As an elaboration of the original model it should not violate any important assumption of that model. In particular it should still yield the principle prediction so far tested, prediction 1 (Dawkins 1969).

Rooted in these two rules, the attention threshold model yields a range of further predictions in fields where the original model could say nothing; for this the assumptions must be expressed algebraically. It is convenient to do this in terms of a particular hypothetical example.

## A Hypothetical Example

Domestic chicks, in choice tests between pairs of stimuli, prefer to peck at circles rather than triangles, and at red objects rather than green ones (Curtius 1954). Suppose that the system concerned with colour is higher in the hierarchy than that concerned with shape (Fig. 1). Other systems will be ignored except the casting vote system which will be taken as that concerned with stimulus position, and as the lowest in the hierarchy.

We shall use the following terms:

w—probability of sequence of events beginning by attention to colour system

s—probability of sequence of events beginning by attention to shape system

p—probability of sequence of events beginning by attention to position system

r—proportion of time spent by V of colour system between red's and green's threshold

g—proportion of time spent by V of colour system above green's threshold

c—proportion of time spent by V of shape system between circle's and triangle's threshold

t—proportion of time spent by V of shape system above triangle's threshold.

It is assumed that when the animal attends to the position system it chooses the physically nearest stimulus regardless of colour or shape. We shall also assume for convenience that when the animal switches its attention from the colour system, it always switches to the shape system.

Consider a choice test between a red circle and a green triangle. The probability of the animal's choosing the red circle is the probability of its choosing red given that it is attending to colour, plus the probability of its choosing the circle given that it is attending to shape, plus $\frac{1}{2}$ given that it is attending to position, since the nearest stimulus is equally likely to be either the red circle or the green triangle (Dawkins 1969). That is

$$w\{r + g[c + \tfrac{1}{2}(1 - c)]\} + s(c + \tfrac{1}{2}t) + \tfrac{1}{2}p.$$

In the same way the probability of the green triangle's being chosen can be calculated as $wg(1 - c) + \frac{1}{2}st + \frac{1}{2}p$, and therefore the proportion of choices of the red circle rather than

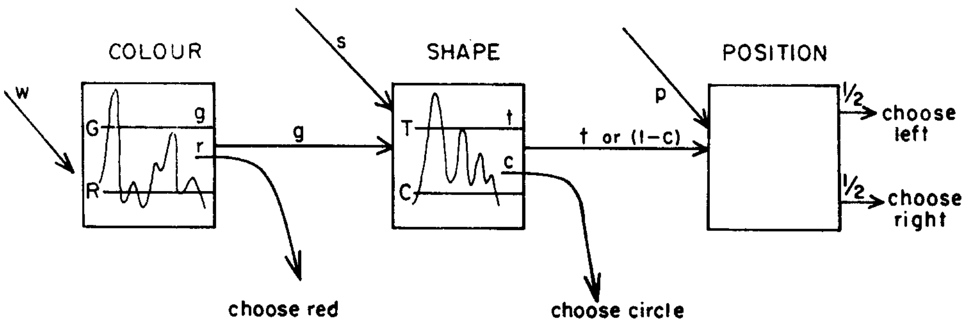


Fig. 1. Diagram of attention threshold model. Three systems are shown, dominance order from left to right. The position system is the casting vote system. The boxes representing the other two systems each contain a picture of their own specific variable V, and thresholds corresponding to the stimuli (red, green, circle, triangle). The small letters (or numbers) on arrows represent the probabilities that the events signified by those arrows will take place. Arrows leading into boxes from upper left signify initial attention to that system. Arrows leading from one box to another represent switches in attention. Other arrows leading out of boxes signify overt choices. Further details in text and Table I.

the green triangle, or percentage preference, should be

$$\frac{w[2r + g(1 + c)] + s(2c + t) + p.}{2w(r + g) + 2s(c + t) + 2p}$$

Two colours and two shapes can be combined in four different stimuli, and these stimuli can be presented in six possible pair choice tests, of which we have just considered only one. Table I gives the percentage preferences called $P_1$ to $P_6$ worked out in the same way for all six choices.

**Table I. $P_1$ to $P_6$, the 6 Hypothetical Percentage Preferences for the 6 Possible Pair Choice Tests Using Combinations of Red or Green, Circle or Triangle**

| P | Stimuli | Description of choice | Percentage preference |
|---|---|---|---|
| $P_1$ | Red circle v. green circle | Colour choice, both good shape | $\frac{w(2r + g) + s(c + t) + p}{2w(r + g) + 2s(c + t) + 2p}$ |
| $P_2$ | Red triangle v. green triangle | Colour choice, both bad shape | $\frac{w(2r + g) + st + p}{2w(r + g) + 2st + 2p}$ |
| $P_3$ | Red circle v. red triangle | Shape choice, both good colour | $\frac{w(r + g)(c + 1) + s(2c + t) + p}{2w(r + g) + 2s(c + t) + 2p}$ |
| $P_4$ | Green circle v. green triangle | Shape choice, both bad colour | $\frac{wg(c + 1) + s(2c + t) + p}{2wg + 2s(c + t) + 2p}$ |
| $P_5$ | Red circle v. green triangle | Colour and shape choice. Additivity | $\frac{w[2r + g(c + 1)] + s(2c+t) + p}{2w(r + g) + 2s(c + t) + 2p}$ |
| $P_6$ | Red triangle v. green circle | Colour and shape choice. Opposition | $\frac{w[2r + g(1 - c)] + st + p}{2w(r + g) + 2s(c + t) + 2p}$ |

$P_5$ is the one already considered.

These expressions are not of course testable predictions in themselves, but they can be combined to give testable predictions. For example it can be shown that $P_6 = 2(P_1P_4 - P_4) + 1$. This is one of the predictions now to be discussed. Their deductions will not be given in detail; they can easily be verified by substitution. We shall continue to speak in terms of the hypothetical example, but the predictions, like the model itself, may be applied more generally.

## Prediction About Effect of Irrelevant Cues

Table I gives two different colour preference tests, and two different shape tests. Thus $P_1$ is the red/green percentage preference when both stimuli are circular, and $P_2$ is the same colour preference with both stimuli triangular. Should we expect the strength of the colour preference to be the same or different under these two conditions? This is clearly an important practical question for a student of colour preference. Common sense might recommend to him that he should do everything possible to maximize the response tendency of his animal, including using optimal stimuli with respect to irrelevant cues. However the attention threshold model suggests exactly the opposite; it can be shown that $P_2$ is larger than $P_1$, and $P_4$ is larger than $P_3$ (except under certain special circumstances when they should be equal). To express the general prediction, a percentage preference involving a particular stimulus difference should be higher when both stimuli are of low value according to irrelevant cues, than when both stimuli are of high value according to irrelevant cues. This does make some subjective sense. When given a choice between two extremely desirable and in general similar alternatives, one may tend to ignore any small differences which there may be between them.

Nissen & Jenkins (1943) trained chimpanzees on a simultaneous discrimination problem with two cues, brightness and size relevant, in the equivalent of the $P_5$ additivity situation of Table I. They were then given choice tests with each cue separately relevant. The important point here is that these single cue tests were carried out under both irrelevant cue conditions. Thus the brightness preference was measured separately with both stimuli large and with both stimuli small, and the size preference was measured separately with both stimuli bright and with both stimuli dark.

The prediction is confirmed significantly (Table II $P<0{\cdot}005$, Wilcoxon matched pairs test, 1-tailed). I tested the prediction on domestic

**Table II. Test of Irrelevant Cue Prediction on Chimpanzees** (Data from Nissen & Jenkins 1943)

| Subjects | Relevant cue | Irrelevant cue | |
|---|---|---|---|
| | | Both positive | Both negative |
| Adults | Brightness | 76·8 | 85·5 |
| ,, | Size | 75·5 | 79·5 |
| Juveniles | Brightness | 66·5 | 74·5 |
| ,, | Size | 67·8 | 85·5 |

The figures are percentage numbers of choices of the positive (i.e. preferred) stimulus when the stimuli differed according to the specified relevant cue. They are separated according to whether both stimuli were positive or negative according to the irrelevant cue. The prediction is that the 'both negative' figures should be larger than the corresponding 'both positive' ones.

chicks' pecking, in the form of the hypothesis that the percentage preference for blue over red should be higher when both stimuli are flat discs than when both stimuli are solid hemispheres (hemispheres are preferred to discs (Fantz 1958; Dawkins 1968)). For the peck counting method see Dawkins 1969.

Again the prediction was confirmed (Table III, $P<0{\cdot}05$, Mann-Whitney U test, 1-tailed), but not so decisively.

**Table III. Test of Irrelevant Cue Prediction on Domestic Chicks**

| | Both solid ('positive') | Both flat ('negative') |
|---|---|---|
| First batch | 82·6 | 90·3 |
| Second batch | 78·6 | 85·6 |

The figures are (for two separate batches of chicks) the mean percentage numbers of pecks at blue rather than red, separated according to whether both stimuli were solid or flat. It is predicted that the 'both flat' percentage preferences should be larger than the 'both solid' ones.

## Prediction About Additivity of Cues ('Heterogeneous Summation')

Knowing the percentage preference for red objects over green ones, and that for circles over triangles, can we predict the percentage preference for a red circle over a green triangle? This is a question about additivity of cues (cf. 'heterogeneous summation', Seitz 1940).

Hara & Warren (1961) asked an equivalent question, using cats. They trained their cats separately on brightness, size and shape discriminations, and then measured choice probabilities when combinations of these cues were made simultaneously available. They found a good fit to a formula

$$P_{a+b} = 2(P_a + P_b - P_a P_b) - 1,$$

where $P_a$ and $P_b$ were the percentage preferences in two single cue tests, and $P_{a+b}$ was the percentage preference when the two cues were combined. An elaboration of the same formula successfully predicted the effects of combining all three cues. They do not provide any detailed rationale for the formula, and their use of it is presumably ad hoc.

The formula is the same as the one I later used in a different context, and called prediction 1 (Dawkins 1969). It may be also written more briefly $Q_{a+b} = 2Q_a Q_b$, where $Q = 1-P$. For convenience it will be called the prediction 1 formula here, though it should on no account be confused with prediction 1 itself.

McGonigle (1967) did similar experiments on rats, and also obtained a good fit to the prediction 1 formula. Sutherland & Holgate (1966), also using rats, mention the prediction 1 formula but find that their data fit another formula better, namely

$$P_{a+b} = P_a P_b / (P_a P_b + (1-P_a)(1 - P_b)).$$

This formula has been called the Product Rule.

What does the attention threshold model predict about additivity of cues? The answer depends upon the qualities of the stimuli with respect to irrelevant cues in the single cue tests, for example on whether we test the red/green preference with both stimuli round or triangular. Taking the expressions in Table I, is there a formula by which we can predict $P_5$ from [$P_1$ or $P_2$] and [$P_3$ or $P_4$]? A precise prediction has been discovered for only one of the four possible combinations, namely

$$P_5 = 2(P_1 + P_4 - P_1 P_4) - 1.$$

This is of course the 'prediction 1 formula' found by the above authors to fit their experimental data. For the other three combinations it is possible to predict the direction in which the prediction 1 formula should err. Thus

$$P_5 \ll 2(P_2 + P_3 - P_2 P_3) - 1;$$
$$P_5 \ll 2(P_2 + P_4 - P_2 P_4) - 1;$$
$$P_5 \gg 2(P_1 + P_3 - P_1 P_3) - 1.$$

In the latter case numerical substitution shows that the formula called the product rule approximates the model's prediction in practice, though it does not follow from it in theory.

The published data do not permit us to decide which variant of our prediction is applicable. However numerical substitution shows that in practice the four predictions give rather similar results. We may conclude that the available data on cue additivity support the attention threshold model.

**Prediction About Opposition of Cues ('Heterogeneous Subtraction')**

We have just considered the effects of positively combining two preferences concerned with different cues. What does the model predict when we *oppose* two such preferences—when we pit say a colour preference against a shape preference? If red is preferred to green, and circles to triangles, what will happen in a choice between a red triangle and a green circle?

Hara & Warren (1961) and McGonigle (1967) in the studies already mentioned obtained answers to this type of question. An important feature of their method was a careful psychophysical scaling of stimuli so that in the single cue tests the percentage preferences were identical in magnitude for all three cues—brightness, shape and size. When pairs of the cues were opposed both studies gave the same paradoxical result. Instead of showing no preference the animals tended to show a bias in favour of the preference mediated by one of the two cues. This was in spite of the fact that in single cue tests the two preferences were equally strong—standardised at for example exactly 80 per cent—and in spite of the fact that the two preferences contributed equally strongly to the cue additivity effect.

As already noted, the cue additivity effect shown by these studies was precisely as expected by the attention threshold model, and this includes the symmetrical nature of the contribution of all the cues. It is extremely interesting to find that the model also predicts the surprising asymmetrical dominance effect shown when cues are opposed.

From Table I it can be shown that

$$P_6 = 2(P_1P_4 - P_4) + 1.$$

Once again no precise predictions have been found for the other possible combinations of $P_1$, $P_2$, $P_3$ and $P_4$, and we are not told which combinations were used in the published studies, but again numerical substitution shows that in all cases the formula approximates the true prediction of the model. The striking thing about this formula is that it is *asymmetrical*: $P_4$ appears in it twice, while $P_1$ occurs only once. This means that even if $P_1 = P_4$, $P_6$ will be larger than 50 per cent. For example if an 80 per cent preference is pitted against another 80 per cent preference on a different cue, the model predicts a percentage preference in favour of one cue (the one whose system is higher in the hierarchy or 'dominant') of around 68 per cent; the two preferences should *not* cancel each other out as common sense might expect.

In the case of Hara and Warren's data there is even a fair quantitative correspondence between observed and predicted percentage preferences. (For single cue preferences of 80 per cent, predicted opposition preference = 68 per cent, observed results 68 per cent, 67 per cent and 58 per cent, mean 64·3 per cent. For single cue preferences of 70 per cent, predicted opposition preference = 58 per cent.; observed results 54 per cent, 71 per cent and 49 per cent, mean 58·0 per cent!). However in view of the high variation, and the fact that a quantitative fit is not obtained with McGonigle's (1967) data, these details should not be taken seriously. It may be that there was individual variation in the V/threshold system hierarchies. The important thing is that qualitatively both studies show the paradoxical asymmetry effect just as expected by the model.

The model even predicts a slight dominance effect if a 70 per cent preference on a dominant cue is pitted against an 80 per cent preference on a subordinate cue. The preference in favour of the dominant cue should in this case be only 52 per cent. This has not been tested as far as I know.

Nissen & Jenkins (1943) in the study on learned brightness and size preferences in chimpanzees already mentioned also did cue opposition tests. They did not psychophysically scale their stimuli, so direct testing of the qualitative asymmetry prediction is not possible. However they do give all four single cue percentage preferences precisely, so we can test the prediction quantitatively. First we must make an assumption as to which of the two systems, brightness or size, is higher in the hierarchy or 'dominant'. Since we have no a priori way of deciding which of the two possible assumptions to make, we shall make both separately, testing the prediction twice. Our expectation is that in one of these two cases the prediction should prove accurate; in the other case it should prove wrong.

This expectation is well fulfilled (Fig. 2). While the assumption that the size system is dominant clearly leads to a wrong prediction,

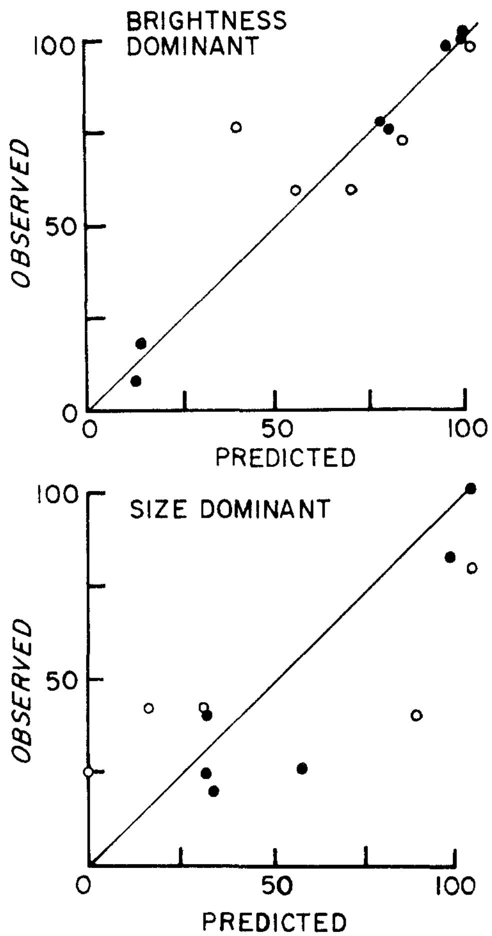


Fig. 2. Opposition prediction tested on chimpanzees (data from Nissen & Jenkins 1943). The graphs are scatter diagrams of observed $P_6$ against predicted (i.e. $2(P_1P_4 - P_4) + 1$, under two different assumptions about cue dominance. It was predicted that one of the two assumptions should give a good fit (points close to 45° line), while the other should not. The N for the solid circles (adult animals) is considerably larger than that for the open circles (juvenile animals). The solid circles therefore represent a more reliable test of the prediction.

on the alternative assumption that brightness is dominant to size, the cue opposition formula, $P_6 = 2(P_1P_4 - P_4) + 1$ predicts the observed data well.

Again we may conclude that the attention threshold model has been successful in explaining experimental results.

**Other Consequences of the Model**

Assuming that attention waves take a measurable time to pass down the hierarchy, we should predict that choices involving a relatively dominant system should have a relatively short latency. As we have seen, cue opposition tests provide a way of discovering the dominance relations of systems. We therefore expect that in single cue tests, choices involving cues shown to be dominant in cue opposition tests should be made relatively fast, and this even if the percentage preferences are equalised by psychophysical scaling. McGonigle (1967) measured choice latencies of his rats in the Lashley Jumping Stand, and found precisely this result. The other authors do not publish latency results.

Other predictions about response latency follow from the model. Thus for any given stimulus pair, the mean latency of 'wrong' decisions, i.e. choices of the less preferred stimulus, should be greater than the mean latency of 'correct' choices. This follows because all 'wrong' choices are made after a switch in attention from one system to another, while only some 'correct' choices are. Such a result was obtained by Henmon (1911) in experiments on the judging of lengths of lines by man. Not surprisingly the data do not provide support for the more detailed form of the prediction, namely that the latencies of correct choices should be bimodally distributed, the longer mode coinciding with the single mode of the distribution of latencies of wrong choices.

A similar prediction, which makes sense subjectively, is that choices between stimuli which are close in the preference order should have longer latencies than choices between stimuli where the preference is strong. There is evidence for this in experiments on man (Dashiell 1937; Barker 1942; Guilford 1954).

**Discussion**

A model should be judged largely by its success in predicting results. The success of the attention threshold model may appear somewhat marred by the fact that the experimental results were obtained before the 'predictions' were made. This is a wrong impression however; the assumptions of the model were not in any way adjusted to fit these facts, but were framed so as to preserve the essential properties of the parent choice threshold model, while providing an explanation for the otherwise rather puzzling 'suprathreshold indecision' of that parent model (Dawkins 1969). The fact that the attention model thus constituted was able to make other predictions, was ancillary.

The assessment of a model according to the success of its predictions should take account of a quality which may be called Predictive Information Value. This is a measure of the extent to which the model 'commits itself' or 'sticks its neck out'; its statistical improbability or vulnerability to disproof. A model whose predictions are nearly obviously true is of little value.

Factors tending towards a high predictive information value are:

1. Yielding of predictions which specify one or a few out of a wide range of possibilities: the predictions about additivity and opposition of cues (and also prediction 1—Dawkins 1969) have high information value since they are quantitatively precise and should be easy to disprove. The prediction about irrelevant cues on the other hand has low information value in the sense that it merely specifies that one quantity should be larger than another, and it therefore has a good chance of being right in any case.

2. Yielding a large number of separate predictions: the attention threshold model and the parent choice threshold model are quite prolific of predictions which are not logically equivalent to each other. The several predictions tested in these papers are only a beginning.

3. Yielding of predictions which are not expected by common sense: this factor partly includes the other two. The prediction about opposition of cues is all the more interesting because it seems paradoxical (McGonigle 1967). The prediction about additivity of cues is fully compatible with common sense qualitatively, though it is quantitatively more precise (see 1 above).

The more numerous (2), quantitatively precise (1), and subjectively surprising (3) the successful predictions of a model are, the less likely is it that alternative explanations for the observed results will be found.

From the assumption that suprathreshold indecision results in a switch in attention, it follows that animals should spend more time attending to a given cue if the available stimuli are far apart in preference order by that cue, than if they are close. For example a chick whose order of preference is orange/blue/green, should attend to colour more if presented with orange and green than if presented with orange and blue. The consequences of this for rates of discrimination learning are outside the scope of this paper. However its possible relevance to speculations about the functional significance of selective responsiveness (Quine & Cullen 1964) may be mentioned.

It seems possible that a functional question such as 'Why does the chick prefer blue to green?' would be better replaced by 'Why does the chick have strong colour preferences?' It might be that there is little importance in which colours the animal happens to prefer, provided it prefers something. From what we have just seen this could be the case, if there were some advantage in the chick's having a high tendency to *attend* to colour rather than to other cues. It might for instance be a good thing to learn about food in terms of colour.

## Summary

1. The attention threshold model is a modified version of a previously proposed choice model called the choice threshold model. It arose as an attempt to explain a puzzling feature of the original model.

2. The assumptions of the attention threshold model are listed. These seem quite complex, but the complexity is needed to preserve the predictive properties of the original model.

3. The assumptions of the attention threshold model are given formal algebraic expression with respect to a particular hypothetical example.

4. Predictions which follow from this algebraic treatment are discussed and compared with experimental evidence, mostly taken from the literature.

These are: (a) a prediction about the effect of irrelevant cues on preference strength; (b) a prediction about additivity of cues ('heterogeneous summation'); (c) a prediction about opposition of cues ('heterogeneous subtraction'); and (d) various predictions about response latency.

5. The model is assessed according to the success of its predictions.

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