Available online at www.sciencedirect.com
SCIENCE DIRECT®
Behavioural Processes 61 (2003) 47–56
BEHAVIOURAL PROCESSES
www.elsevier.com/locate/behavproc

Manipulating decision processes in the human scalar timing system

J.H. Wearden*, Rachel Grindrod

Department of Psychology, Manchester University, Manchester M13 9PL, UK

Received 5 April 2002; received in revised form 1 October 2002; accepted 3 October 2002

Abstract

Two experiments attempted to manipulate the decision processes used in a temporal generalisation task with humans. In Experiment 1, payoffs (points awarded or deducted) were used to try to alter behaviour when the standard duration was 400 ms, and the comparison durations ranged from 100 to 700 ms in 100 ms steps. Two conditions which either encouraged or discouraged the subject to identify a comparison duration as the standard were compared with a neutral condition. Encouraging identifications of the standard increased the proportion of identifications of the standard, whereas the discouraging manipulation had more ambiguous effects. Using the "modified Church and Gibbon" model, it was shown that the effect of the encourage manipulation was an increase in the response threshold, consistent with the information-processing version of scalar timing theory. A second experiment compared encourage and discourage manipulations with a more difficult discrimination (comparison durations spaced in 50 ms steps around the 400 ms standard), and with more distinct payoff differences for the different conditions. Behavioural effects were much more marked in Experiment 2, with the encourage condition producing more identifications of a comparison duration as the standard for all comparison durations except the shortest, compared with the discourage condition. Modelling showed that the main theoretical difference between the two conditions was in a change in the response threshold, in a manner consistent with the scalar timing model.

Keywords: Scalar timing; Temporal generalisation; Payoff manipulations; Temporal sensitivity; Decision processes; Humans

1. Introduction

As discussed previously in this journal (Allan, 1998), one of the most notable success stories in the history of animal/human comparative psychology has been the application of *scalar timing theory* (or scalar expectancy theory (SET); Gibbon et al., 1984), initially developed as an account of animal timing, to timing behaviour in humans.

The SET system proposes that timed behaviour is derived from an interaction of processes at three levels. The first is a clock level, where "raw" time representations are derived from an internal clock consisting of a pacemaker which is connected by a switch to an accumulator which stores pacemaker output. The second level consists of two sorts of memories of duration. One of these (working memory) reflects the contents of the accumulator more or less directly (and in fact is merged with the accumulator in some recent treatments of SET). The second (reference memory) stores "important" times, such as those associated with reinforcement in experiments with animals, or

* Corresponding author.
E-mail address: wearden@psy.man.ac.uk (J.H. Wearden).

0376-6357/02/$ – see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0376-6357(02)00159-6

times identified as standards of some sort in experiments with humans. The final level is a decision process level, where comparisons are made between the contents of accumulator/working memory, and one or more samples derived from the reference memory.

The whole system operating together is needed to produce timed behaviour, so if different subject populations, or the same subjects in different conditions, exhibit different behaviours the problem arises of attributing these behaviours to differences in one part of the SET system rather than another. In addition, to fit any particular set of data, the clock, memory, and decision processes can be adjusted as required, thereby causing problems of testability of the model (Wearden, 1999) and giving SET an "erector kit" aspect (Staddon and Higa, 1999) which has attracted criticism.

One way to disambiguate the operation of the SET system is to try to manipulate its different parts separately, leaving everything else the same. The most conspicuous success of this "isolation" method has come from manipulations which have attempted to change the speed of the pacemaker of the internal clock. Studies using rats have manipulated pacemaker speed with drugs (Maricq et al., 1981; Meck, 1983), and more recent work has used a discovery by Treisman et al. (1990) to change pacemaker speed in humans. Treisman et al. (1990) found that presenting humans with a train of repetitive clicks or flashes made them behave as if the pacemaker of their internal clock had been speeded up. Repetitive stimulation has been used to change clock speed in adult humans in a number of articles (Burle and Casini, 2001; Penton-Voak et al., 1996; Wearden et al., 1999), and it has recently been shown that even children as young as 3 years will exhibit this effect (Droit-Volet and Wearden, 2002).

The memory level of the SET system has received much less attention, although Meck (1983) apparently affected the contents of rats' reference memory using drugs, and some recent articles (Allan and Gerhardt, 2001; Wearden and Bray, 2001) have investigated human timing in the probable absence of reference memory.

The decision level of the SET system has received the least attention even though from the theoretical point of view it is often of central importance in explanations of behaviour. For example, differences between the performance of rats and pigeons, and humans, on temporal bisection tasks have been attributed mostly to differences in the decision processes used (Wearden, 1991a; Wearden et al., 1997a,b). In general, however, a problem is that the decision processes used to model performance on some task are invented in a rather ad hoc (but often very plausible) manner, rather than being manipulated or controlled.

To our knowledge, only one previous study (Wearden and Culpin, 1998) has reported the results of attempts to manipulate decision processes in human timing, using the theoretical framework of SET, and we will discuss their results in more detail later. The purpose of the present article is to report two experiments which use payoffs (the consequences of various sorts of timing decisions) to try to manipulate the decision processes that people are using on a simple timing task. In our Experiments 1 and 2, the different conditions differ only in the response payoffs, and all stimuli to be timed remain identical, so presumably the clock and memory processes in operation in the different conditions would also be expected to be identical.

The task used in both our experiments is the standard form of temporal generalisation for humans, derived by Wearden (1992) from an experiment with rats by Church and Gibbon (1982). In temporal generalisation, the experimental session begins with a small number of presentations of a duration identified as a standard, for example, a tone 400 ms long, a duration too short (as are all the durations usually used in such experiments) to make chronometric counting useful to the subject. Then, comparison stimuli of various durations are presented (e.g. ranging from 100 to 700 ms in 100 ms steps), and the subject's task is to judge whether each presented duration is or is not the standard (a YES or NO response). The response is usually followed by accurate performance-related feedback.

The result of such an experiment is a temporal generalisation gradient in the form of the proportion of YES responses given to each presented comparison duration. Such gradients usually peak at the duration which is equal to the standard and, in humans adults at least, are usually asymmetrical in that stimuli longer than the standard are confused with it more often than stimuli shorter by the same amount (i.e. 500 ms generates more YES responses than 300 ms, when a 400 ms standard is used). For examples of such data from human adults see Wearden (1991b, 1992), Wearden and Towse (1994), Wearden et al. (1997b,c) and McCormack et al. (1999).

The theoretical analysis of such generalisation gradients in humans derives from a very similar analysis of data from animals provided by Church and Gibbon (1982), and the model commonly used is known as the modified Church and Gibbon model (MCG model; see Wearden, 1992). The MCG model uses all three parts of the SET system. The standard duration is supposed to be stored in reference memory, and be represented as a Gaussian distribution with some mean (s), which is on average accurate (i.e. 400 ms when the standard duration is 400 ms), and some coefficient of variation (c). Larger c values represent more variable temporal memories. The comparison duration presented on a particular trial (t), is assumed to be timed without error. To produce behaviour, the MCG model assumes that people respond YES when $\mathrm{abs}(s^* - t)/t < b^*$. Here, abs denotes absolute value, t is the just-presented comparison duration, s^* is a sample from the reference memory (which differs from trial to trial around the mean s, with the distribution having a coefficient of variation of c), and b^* is a threshold value sampled from a Gaussian distribution with a mean b, and some trial by trial variance.

The two parameters of principal interest are: c, the "fuzziness" of the temporal memory, and b, the threshold mean. Of these two, b is part of the decision process alone, and might be affected if decision processes are altered. How could this be done? Suppose that a 400 ms standard duration is used, with comparisons ranging from 100 to 700 ms. One method that might alter decision processes is to vary payoffs for various sorts of responses. Responding YES when a 400 ms duration has been presented is a *hit*, whereas this response after other durations is a *false positive*. Conversely, responding NO after 400 ms is a *miss*, and this response after other durations is a *correct rejection*. Suppose that subjects are given points (added for correct responses: hits and correct rejections; deducted for incorrect responses: misses and false positives), but that the points added and subtracted are not symmetrical. That is, YES responses could be encouraged by awarding more points for a hit than are awarded for a correct rejection; YES responses could be discouraged giving more points for a correct rejection than for a hit. This type of manipulation is common in perceptual studies using the framework of signal detection theory (Gescheider, 1985), and may be useful in modifying decision processes in the SET framework, when other features of the task are kept constant. If the MCG model is correct in detail, then anything that encouraged YES responses might do so by increasing the threshold (b), whereas a manipulation that discouraged YES responses might decrease b.

It is important to note that the theoretical aim of the present article is to test the "behaviour" of the SET-consistent MCG model when payoff manipulations which might be expected to change responding are used. Any model involving some sort of "threshold" for deciding whether some presented duration was or was not the standard would be expected to model changed behaviour by showing a threshold change; however, within the MCG model, the change should be in the b parameter, without any systematic change in other parameters of the model. A difficulty of some recent models of timing behaviour is that data from some particular experimental condition may be fitted nearly perfectly by a number of different theories (e.g. Wearden and Ferrara, 1995, 1996), so some way of distinguishing the different accounts other than by goodness of fit needs to be used. One potential way to do this is to examine whether the parameters of the model "behave" in appropriate ways as the behaviour of the subjects is changed by variations in procedure. The present investigation aims to test exactly this with respect to the decision mechanism of the MCG model.

2. Experiment 1

Our Experiment 1 was an initial attempt to manipulate the decision processes in temporal generalisation when a consistent duration set was used. Subjects received three conditions in a random order, in all of these the standard was 400 ms, and the comparisons ranged from 100 to 700 ms in 100 ms steps. In one condition (*neutral*) hits and correct rejections were symmetrical, with the one point being added for hits and for correct rejections. The two types of errors (misses and false positives) likewise both resulted in the loss of one point. In the *encourage* condition, YES responses were encouraged by weighting hits more than correct rejections; in the *discourage* condition, correct rejections gained more points than hits. We were interested in two questions. Firstly, what effect, if any, would the payoff manipulations have empirically? Secondly, how would the parameters of the MCG model that best fitted data from the different conditions be affected, if at all, by the payoff changes?

2.1. Method

2.1.1. Subjects

Thirty-seven Manchester University Psychology undergraduates served.

2.1.2. Apparatus

An OPUS 386 (IBM compatible) computer controlled all experimental events, and recorded subjects' responses on the keyboard. The computer speaker produced the tones whose duration had to be judged. The experimental program was written in the MEL language (Psychology Software Tools Inc.) which assured millisecond accuracy for the timing of stimuli and responses.

2.1.3. Procedure

Subjects received the three experimental conditions (neutral, encourage and discourage) in a single experimental session lasting about 45 min. The order of the presentation of the conditions was randomised between subjects. The conditions were identical in all details except for the payoffs arranged for different sorts of responses. Consider first the procedure for the neutral condition. The condition began with four presentations of a 400 ms, 500 Hz tone which was identified explicitly as the standard. Presentations of the standard were separated by random delays ranging between 1000 and 2000 ms, offset to onset. Following this, subjects received five blocks of comparison durations. Each block consisted of eight stimuli, arranged in a random order which varied between blocks and subjects. Two of the stimuli in the block were 400 ms long, the duration of the others was 100, 200, 300, 500, 600 and 700 ms. To produce each comparison duration, the subject responded to a "Press spacebar for next trial" prompt, and this response was followed by a delay drawn randomly from a uniform distribution running from 1000 to 2000 ms. When the stimulus terminated, subjects received the display "Was that the standard duration? Press Y (YES) or N (NO) keys". A response on the key was followed by accurate feedback in all cases (e.g. "Correct, that WAS the standard duration"), which was displayed in the centre of the screen for 1500 ms. This was then followed by another display "You have gained/lost X points", which was displayed for 2000 ms, then the "Press spacebar for next trial" prompt was repeated. Subjects began with 50 points, and for the neutral condition each correct response (hit or correct rejection) added one point ($X = 1$) in the display mentioned above. Each incorrect response (misses and false alarms) deducted one point from the total, and the post-response display was adjusted accordingly.

The procedure for the other conditions was identical in all respects except for one of the payoffs: for the encourage group, a hit resulted in an increase of three points; for the discourage group, a correct rejection resulted in an increase of three points. Other payoffs were as for the neutral condition.

2.2. Results and discussion

Fig. 1 shows temporal generalisation gradients (mean proportion of identifications of a comparison stimulus as the standard, 400 ms, duration, plotted against comparison duration) for the three experimental conditions. The upper panel shows data from the neutral and encourage conditions, the central panel data from the neutral and discourage conditions, and the bottom panel shows the comparison between the encourage and discourage conditions. Data were taken from the last four of the five blocks of comparison durations.

Inspection of the generalisation gradients suggests that they had the normal form for temporal generalisation in humans: all were peaked at the standard, and all were slightly asymmetrical, with comparison durations longer than the standard producing more YES responses than durations shorter by the same amount. Consider next the effect of the payoff manipulation. The data in the upper panel suggest that the effect of attempts to encourage YES responses was an increase in the proportion of such responses to all comparison durations, apart from those most remote from the standard, in the encourage condition compared with the neutral one. Effects of the discourage manipulation, on the other hand, appeared more ambiguous, with some comparison durations resulting in a smaller proportion of YES responses (particularly 400 and 500 ms), compared with the neutral condition, whereas this effect

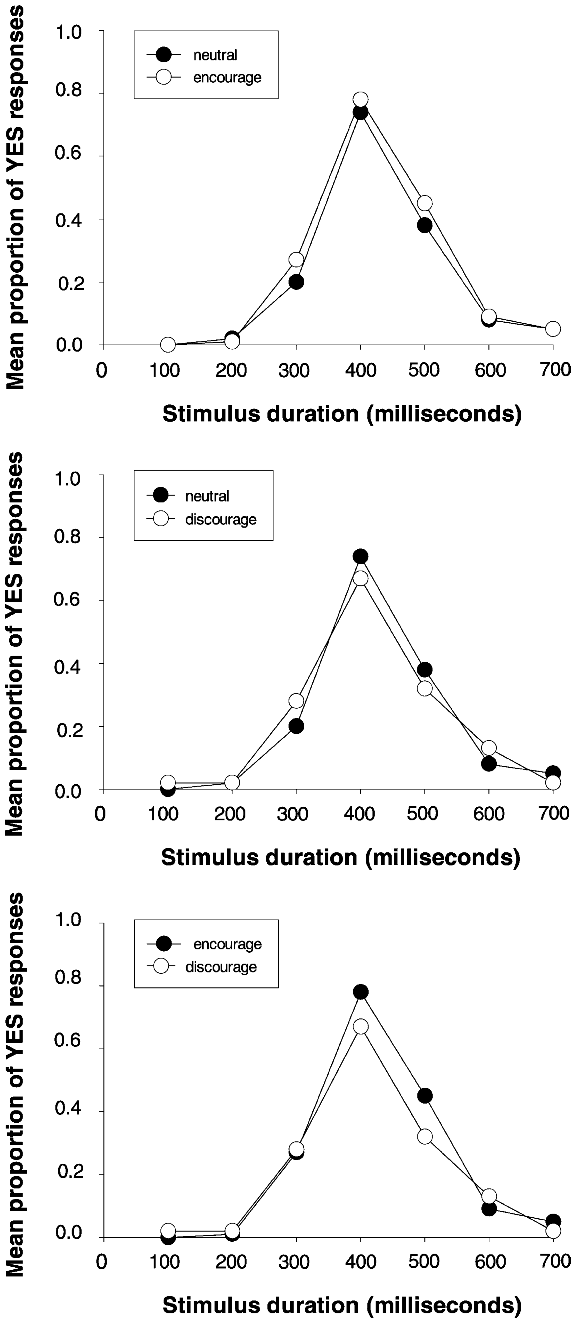

Fig. 1. Temporal generalisation gradients (proportion of identifications of a duration as the standard (YES responses) plotted against comparison stimulus duration) from the three conditions (neutral, encourage and discourage) of Experiment 1. Upper panel: data from neutral and encourage conditions; central panel: data from neutral and discourage conditions; bottom panel: data from encourage and discourage conditions.

is not present after other stimuli. Direct comparison of the encourage and discourage conditions (bottom panel), suggests that the differences between the two conditions were most marked at stimuli close to the standard duration.

This rather complex pattern of results was reflected in the statistical analysis. When all three conditions were considered together in an overall ANOVA, there was no significant overall effect of condition (neutral, encourage, or discourage) [$F(2, 72) = 2.45$, $P = 0.09$], but there was a significant comparison duration × condition interaction [$F(12, 423) = 2.19$, $P < 0.02$], as well as a significant effect of comparison stimulus duration [$F(6, 216) = 172.24$, $P < 0.001$]. This latter result just confirms the fact obvious in Fig. 1 that subjects were highly sensitive to comparison stimulus duration and will not be discussed further.

This pattern of results is in accord with the suggestions derived from inspection of the data in Fig. 1: there was no overall effect of condition (as the different conditions tend to shift the proportion of YES responses in different directions), but the interaction was significant (confirming that the payoff manipulations have some effect, but only at certain comparison durations).

ANOVAs were then conducted on the conditions taken two at a time. Comparison of the encourage and neutral conditions found a significant effect of condition [$F(1, 36) = 5.19$, $P < 0.05$], and a significant effect of comparison stimulus duration [$F(6, 216) = 149.47$, $P < 0.001$], but the condition × comparison duration interaction was not significant [$F(6, 216) = 0.81$, $P = 0.56$]. Comparison of the discourage and neutral conditions found no significant effect of condition [$F(1, 36) = 0.054$, $P = 0.82$], but there was a significant effect of comparison stimulus duration [$F(6, 216) = 129.51$, $P < 0.001$], and a significant comparison duration × condition interaction [$F(6, 216) = 2.70$, $P < 0.02$]. Comparison of the encourage and discourage conditions found no significant effect of condition [$F(1, 36) = 2.49$, $P = 0.12$], but both the effect of comparison stimulus duration [$F(6, 216) = 135.44$, $P < 0.001$], and the condition × comparison stimulus duration [$F(6, 216) = 2.84$, $P < 0.02$], were significant.

Overall, therefore, these data suggest that encouraging YES responses increased the proportion observed after all comparison durations (significant effect of condition), whereas discouraging them had more complex effects, possibly restricted to stimuli close to the standard.

The MCG model, embodied in a computer program written in Visual Basic 6.0 (Microsoft Corporation) was fitted to data from the three conditions. The parameters *c* and *b* were varied over a wide range to minimise the mean absolute deviation between the output of the model and the standard deviation of *b* was always kept at 0.5 of the mean, as in previous models. Table 1 shows the resulting values, as well as the mean absolute deviation, sum of the deviations between the model output and data divided by seven, the number of data points. Fig. 2 shows the fits of the model to data, with results being shown separately for the neutral, encourage, and discourage conditions (upper, middle and bottom panels of Fig. 2).

Consider the parameter values shown in Table 1. The encourage/neutral difference is, according to the fit of the MCG model, entirely accounted for by an increase in *b*, the response threshold, with exactly the same *c* value (memory variance) being needed in the neutral and encourage conditions. Effects of the discourage manipulation were more complex, as both a slight increase in *c*, and a slight decrease in b were needed to fit data.

The conclusions to be drawn from Experiment 1 are fairly straightforward. Encouraging YES responses by changing payoffs significantly increased the proportion of such responses produced (compared with

Table 1
Parameter values for the fits of the MCG model to data from the different conditions in Experiments 1 and 2

	c	*b*	MAD
Experiment 1			
Neutral	0.17	0.18	0.02
Encourage	0.17	0.20	0.02
Discourage	0.18	0.17	0.03
Experiment 2			
Encourage	0.13	0.11	0.03
Discourage	0.12	0.08	0.03

Results are shown in Figs. 2 and 3. Values shown are coefficient of variation of the memory representation of the standard (*c*), the threshold mean (*b*), and mean absolute deviation (MAD), the mean deviation between the data points and the fit of the model. The standard deviation of the threshold was always 0.5 of the mean value.

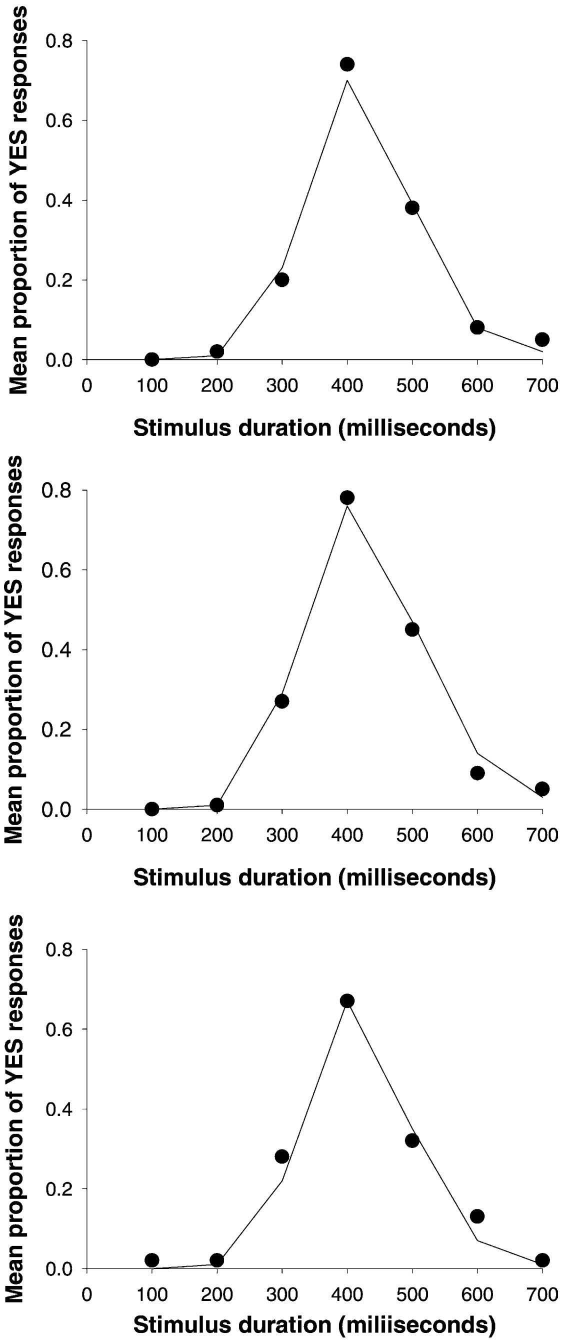

Fig. 2. Data from the three experimental conditions of Experiment 1 (filled circles), and best fitting MCG model for each condition (line). Upper panel: neutral condition; central panel: encourage condition; bottom panel: discourage condition. Parameter values for the fits are shown in Table 1.

the neutral condition), and the effect according to the MCG model (which fitted data well), was an increase in the threshold alone, exactly the effect predicted by the embodiment of the clock/memory/decision structure of SET that the MCG model represents. This result is thus completely consistent with the psychological meaning of the different components of SET. On the other hand, the discourage manipulation had more complex effects: as SET might predict, it decreased the threshold, but it also increased c, an effect which is less easily interpretable.

It is obvious on inspection of Fig. 1 that the effect of the payoff manipulation, while statistically significant, was rather small. Why is this? One possibility was that our payoff manipulation was weak, as only the payoff for hits or correct rejections differed between conditions. An additional possibility is that payoff manipulations with humans are necessarily limited to conditions where the stimuli presented are "ambiguous". As pointed out in a slightly different context, that of operant learning in humans, experimental procedures with humans are game-like social situations with certain rules constraining both the subject and the experimenter (Wearden, 1988). For example, rules of temporal generalisation that the subject obeys are probably that she/he remains attentive, follows experimental instructions to try to identify the standard, and so on. Experimental manipulations on the experimenter's part cannot violate these "demand characteristics" of the experiment without breaking the implicit contract with the subject, with unpredictable consequences for behaviour. For example, some payoff contingency that encouraged the subject to violate their perceptual experience (for example, awarding points for judging that 100 ms is the 400 ms standard) is inconsistent with the avowed aim of the experiment, and cannot be meaningfully used. On the other hand, if the subject is genuinely unsure as to whether some comparison duration is or is not the standard, then payoff manipulations may alter the decision in one way or another. Consistent with this, the clearest differences between the encourage and discourage conditions in Experiment 1 come from judgements made of stimuli close to 400 ms, presumably the most difficult to discriminate from it, where the subject has doubt about the appropriate response (see lowest panel of Fig. 1).

3. Experiment 2

We used these ideas in Experiment 2 to develop a temporal generalisation procedure where the effects of payoff changes would be expected to be more marked. In most details, the procedure of Experiment 2 was identical to that of Experiment 1 (although only encourage and discourage conditions were used), except that the comparison stimuli were made more ambiguous with respect to the 400 ms standard by being more closely spaced around it (50 ms steps instead of the 100 ms steps used in Experiment 1). In addition, the payoffs in the different conditions were made more distinct than in Experiment 1.

3.1. Method

3.1.1. Subjects

Fifteen Manchester University undergraduates served.

3.1.2. Apparatus

A Hyundai 386 computer (IBM compatible) controlled all experimental events and recorded subjects' responses.

3.1.3. Procedure

Subjects received two experimental conditions (encourage and discourage) in a single experimental session. Eight received encourage first, and seven received discourage first. The standard duration was 400 ms, and the comparison stimuli were 250, 300, 350, 400 (presented twice in the block), 450, 500 and 550 ms in duration. For the encourage condition, five points were gained for a hit, and five lost for a miss. The other outcomes resulted in a gain or loss of one point. In the discourage condition, a correct rejection gained five points, whereas a false positive lost five. The other outcomes resulted in a gain or loss of one point. The subject started the session with 100 points. All experimental details not mentioned explicitly were as Experiment 1.

3.2. Results and discussion

The upper panel of Fig. 3 shows data taken from the last four blocks of comparison durations. Inspection of the data suggested that the effect of payoffs was

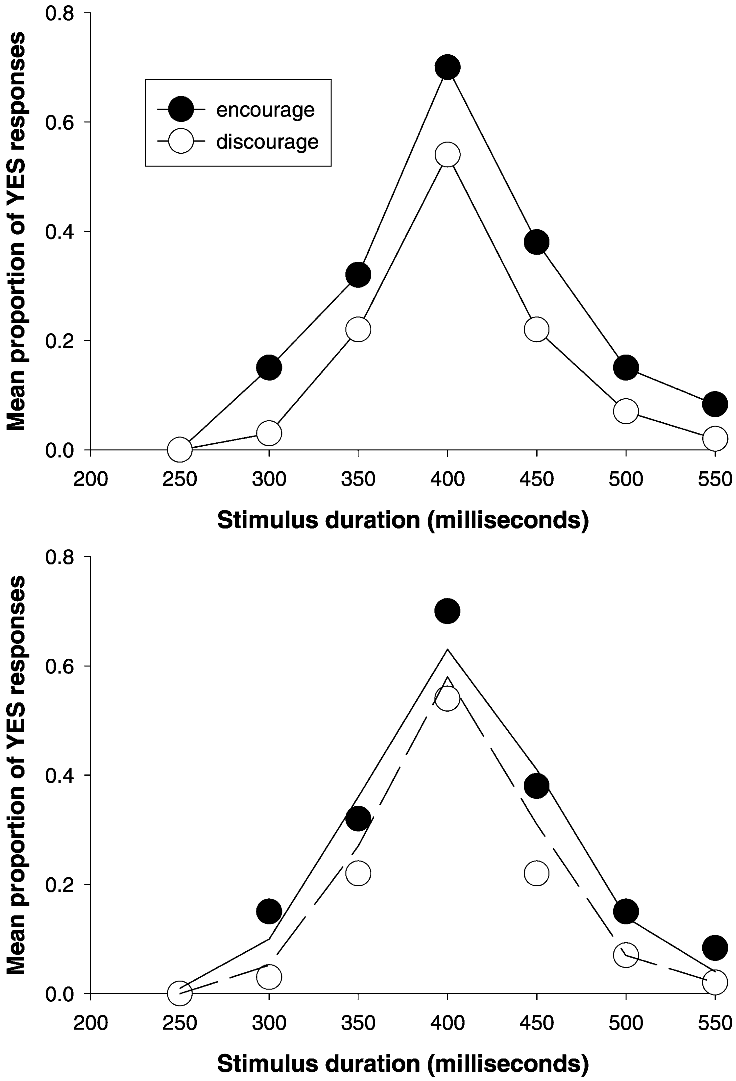

Fig. 3. Upper panel: temporal generalisation gradients from the encourage and discourage conditions of Experiment 2. Lower panel: data from the two experimental conditions of Experiment 2 (encourage: filled circles; discourage: open circles), with the best fitting MCG model for each condition (encourage: solid line; discourage: dashed line). Parameter values for the fits are shown in Table 1.

much more marked than in Experiment 1, with the encourage condition producing a higher proportion of YES responses than the discourage condition, at all durations except the very shortest one.

This suggestion was confirmed by statistical analysis. ANOVA found a significant effect of condition (encourage versus discourage) [$F(1, 14) = 15.74$, $P < 0.01$], and a significant effect of comparison stimulus duration [$F(6, 84) = 34.16$, $P < 0.001$], but no significant condition × comparison duration interaction [$F(6, 84) = 0.81$, $P = 0.49$].

The lower panel of Fig. 3 shows fits of the MCG model to data from the encourage and the discourage conditions, and the lower part of Table 1 shows the parameter values for the fits. Inspection of the parameter values shows that the main effect of the encourage/discourage manipulation was on the threshold for responding YES (b), which was lower in the discourage than encourage condition. The coefficient of variation of the temporal reference memory (*c*) was also slightly lower (0.12 compared with 0.13), but the effect was smaller than the effect on the threshold.

In general, therefore, in accordance with our conjectures, making many of the comparison stimuli more ambiguous with respect to the standard, and making the payoff contingencies more different between conditions, produced a large effect of payoff manipulations in the predicted direction (more YES responses with encourage). Theoretically, the behavioural change was consistent with a difference in the threshold value (*b*) between conditions, confirming the main results of Experiment 1.

4. General discussion

Our two experiments above have both manipulated behaviour on timing tasks using payoffs to affect decision processes and have shown that the effects, particularly increases in the proportion of YES responses occasioned by encourage conditions, can be modelled reasonably well using the principles of SET. Particularly important in this context is the apparent independence of the memory variance parameter (*c*) and the threshold (*b*) in the SET-compatible MCG model. Although the discourage manipulation increased *c* in Experiment 1, it decreased it in Experiment 2, whereas the threshold parameter changed consistently in both experiments, being larger in encourage conditions than discourage ones. Thus, in accordance with the main theoretical aim of the present article, we have demonstrated that the SET-consistent MCG model "behaves" correctly when the behaviour of the subjects is altered.

Although it is not a central focus of the present article, it should be noted that a comparison of the results of Experiments 1 and 2 replicates in principle the findings of Ferrara et al. (1997), that more difficult timing tasks increase temporal sensitivity. This can be illustrated empirically by examining confusions between comparison durations that Experiments 1 and 2 have in common, and the common standard, 400 ms. For example, averaging over the three conditions of Experiment 1, the 300 ms comparison produced 34% of the proportion of YES responses occurring when 400 ms was presented, and 500 ms produced 52% of this proportion. In Experiment 2, on the other hand, the 300 ms comparison produced only 14% of the proportion of YES responses occurring at 400 ms, and the 500 ms comparison produced only 29% of this proportion. Thus, discrimination between stimulus pairs which are identical (300/400 and 500/400 ms) was much better in Experiment 2 than in Experiment 1.

Ferrara et al. (1997) found a similar effect when comparison durations were spaced around a 600 ms standard in either 150 or 75 ms steps. Their theoretical treatment attributed the difference between the conditions to a threshold change (smaller in the 75 ms case). In the present article, however, comparison of the MCG model fits to data from Experiments 1 and 2 indicates that both *c* and *b* were lower in the more difficult conditions (Experiment 2 versus Experiment 1). An increase in temporal sensitivity, similar to smaller *c*, with increasing difficulty of timing tasks was, however, reported by Ferrara et al. (1997) from temporal bisection procedures. It appears, therefore, that increasing discrimination difficulty can affect both response thresholds and temporal sensitivity.

Manipulations of behaviour using payoffs contingent on various sorts of perceptual judgements is commonplace in signal detection theory (e.g. for a review see Gescheider, 1985), where much more sophisticated manipulations than we have used are routine, although such manipulations are unusual in timing studies. Wearden and Culpin (1998) provide one of the few previous examples where the shape of the temporal generalisation gradient was manipulated by changing payoff for different sorts of responses. In their experiment, the standard duration in a temporal generalisation task was 500 ms. Different conditions associated YES responses either at 400 or 600 ms with a particularly severe point loss, and this manipulation changed the shape of the temporal generalisation gradient markedly. For example, when responding "YES" at 400 ms was "punished" by specially heavy point loss, the temporal generalisation gradient was even more skewed to the right than normal (i.e. more skewed towards responding YES to durations longer than the standard), whereas when responding YES at 600 ms was specially punished, the gradient became completely symmetrical.

The present study, and that of Wearden and Culpin (1998), taken together, illustrate how behaviour on timing tasks, where a consistent set of durations is used, can be manipulated, and the present article takes the necessary theoretical step of showing that such behavioural manipulations are accounted for theoretically by changes in response thresholds (i.e. changes in decision mechanisms), in a manner broadly consistent with the structure of SET. This demonstration, while neither counter-intuitive nor even surprising, is necessary for the theoretical development of SET, particularly the important question of the "isolation" of the different components of the SET model (Wearden, 1999). Using the present article as a foundation, more sophisticated manipulations of payoffs, or other response-dependent contingencies, may enable the decision processes of the SET model to be studied in greater detail than ever before.

References

Allan, L.G., 1998. The influence of the scalar timing model on human timing research. Behav. Process. 44, 101–117.

Allan, L.G., Gerhardt, K., 2001. Temporal bisection with trial referents. Percept. Psychophys. 63, 524–540.

Burle, B., Casini, L., 2001. Dissociation between activation and attention effects in time estimation: implications for clock models. J. Exp. Psychol. Hum. Percept. Perform. 27, 195–205.

Church, R.M., Gibbon, J., 1982. Temporal generalization. J. Exp. Psychol. Anim. Behav. Process. 8, 165–186.

Droit-Volet, S., Wearden, J., 2002. Speeding up an internal clock in children? Effects of visual flicker on subjective duration. Q. J. Exp. Psychol. 55B, 193–211.

Ferrara, A., Lejeune, H., Wearden, J.H., 1997. Changing sensitivity to duration in human scalar timing: an experiment, a review, and some possible explanations. Q. J. Exp. Psychol. 50B, 217–237.

Gescheider, G.A., 1985. Psychophysics: Method, Theory, and Application, 2nd ed. Lawrence Erlbaum, Hillsdale, 295 pp.

Gibbon, J., Church, R.M., Meck, W., 1984. Scalar timing in memory. In: Gibbon, J., Allan, L. (Eds.), Annals of the New York Academy of Sciences: Timing and Time Perception, vol. 423. New York Academy of Sciences, New York, pp. 52–77.

Maricq, A.V., Roberts, S., Church, R.M., 1981. Metamphetamine and time estimation. J. Exp. Psychol. Anim. Behav. Process. 7, 18–30.

McCormack, T., Brown, G.D.A., Maylor, E.A., Darby, A., Green, D., 1999. Developmental changes in time estimation: comparing childhood and old age. Dev. Psychol. 35, 1143–1155.

Meck, W.H., 1983. Selective adjustment of the speed of internal clock and memory processes. J. Exp. Psychol. Anim. Behav. Process. 9, 171–201.

Penton-Voak, I.S., Edwards, H., Percival, A., Wearden, J.H., 1996. Speeding up an internal clock in humans? Effects of click trains on subjective duration. J. Exp. Psychol. Anim. Behav. Process. 22, 307–320.

Staddon, J.E.R., Higa, J., 1999. Time and memory: toward a pacemaker-free theory of interval timing. J. Exp. Anal. Behav. 71, 215–251.

Treisman, M., Faulkner, A., Naish, P.L.N., Brogan, D., 1990. The internal clock: evidence for a temporal oscillator underlying time perception with some estimates of its characteristic frequency. Perception 19, 705–748.

Wearden, J.H., 1988. Some neglected problems in the analysis of human operant behavior. In: Davey, G., Cullen, C. (Eds.), Human Operant Conditioning and Behavior Modification. Wiley, Chichester, pp. 197–224.

Wearden, J.H., 1991a. Human performance on an analogue of an interval bisection task. Q. J. Exp. Psychol. 43B, 59–81.

Wearden, J.H., 1991b. Do humans possess an internal clock with scalar timing properties? Learn. Motiv. 22, 59–83.

Wearden, J.H., 1992. Temporal generalization in humans. J. Exp. Psychol. Anim. Behav. Process. 18, 134–144.

Wearden, J.H., 1999. "Beyond the fields we know . . . ": exploring and developing scalar timing theory. Behav. Process. 45, 3–21.

Wearden, J.H., Bray, S., 2001. Scalar timing without reference memory: episodic temporal generalization and bisection in humans. Q. J. Exp. Psychol. 54B, 289–310.

Wearden, J.H., Culpin, V., 1998. Exploring scalar timing theory with human subjects. In: DeKeyser, V., d'Ydewalle, G., Vandierendonck, A. (Eds.), Time and the Dynamic Control of Behavior. Hogrefe and Huber, Gottingen, pp. 33–49.

Wearden, J.H., Ferrara, A., 1995. Stimulus spacing effects in temporal bisection by humans. Q. J. Exp. Psychol. 48B, 289–310.

Wearden, J.H., Ferrara, A., 1996. Stimulus range effects in temporal bisection by humans. Q. J. Exp. Psychol. 49B, 24–44.

Wearden, J.H., Towse, J., 1994. Temporal generalization in humans: three further studies. Behav. Process. 32, 247–264.

Wearden, J.H., Rogers, P., Thomas, R., 1997a. Temporal bisection in humans with longer stimulus durations. Q. J. Exp. Psychol. 50B, 79–94.

Wearden, J.H., Wearden, A.J., Rabbitt, P., 1997b. Age and IQ effects on stimulus and response timing. J. Exp. Psychol. Hum. Percept. Perform. 23, 962–979.

Wearden, J.H., Denovan, L., Fakhri, M., Haworth, R., 1997c. Scalar timing in temporal generalization in humans with longer stimulus durations. J. Exp. Psychol. Anim. Behav. Process. 23, 502–511.

Wearden, J.H., Philpott, K., Win, T., 1999. Speeding up and (. . . relatively . . .) slowing down and internal clock in humans. Behav. Process. 46, 63–73.