# The Effects of Belief and Logic in Syllogistic Reasoning: Evidence from an Eye-Tracking Analysis

**Linden J. Ball** (l.j.ball@derby.ac.uk)
Cognitive and Behavioral Sciences Research Group,
Institute of Behavioural Sciences, University of Derby,
Mickleover, Derby, DE3 5GX, UK

**Jeremy D. Quayle** (j.d.quayle@derby.ac.uk)
Cognitive and Behavioral Sciences Research Group,
Institute of Behavioural Sciences, University of Derby,
Mickleover, Derby, DE3 5GX, UK

**Abstract**

Studies of syllogistic reasoning report a strong non-logical tendency to endorse more believable conclusions than unbelievable conclusions. This *belief bias* effect is found to be stronger with invalid arguments than with valid ones. An experiment is reported in which participants' eye-movements were recorded in order to gain insight into the nature and time course of the reasoning processes associated with experimental manipulations of logical validity and believability. Results are considered in relation to predictions derivable from contemporary accounts of belief bias. The logical status of conclusions was found to influence the duration of gazes, supporting the view that invalid conclusions are more demanding to evaluate than valid ones and the idea that a valid-invalid processing distinction underpins the interaction that is observed between logic and belief. Predictions concerning effects of believability upon gaze behaviour that were derivable from the *mental models* account (e.g., Oakhill & Johnson-Laird, 1985) gained little support. The paper argues for the value of eye-movement analyses in reasoning research as an important adjunct to existing process-tracing techniques.

## Introduction

The syllogism is a deductive reasoning problem comprising two premises and a conclusion (see example given below). The premises feature three terms: two end terms (one in each premise) and a middle term (featured in both premises). A logically valid conclusion to a syllogism is a statement that describes the relationship between the classes of items or individuals referred to by the end terms in a way that is necessarily true. Statements that are simply consistent with the premises but not necessitated by them are invalid. It should be noted that a logical argument is valid by virtue of its *form*, and not because of its content. That is, the actual words or other symbols that could be used as terms within a syllogism are irrelevant when considering validity.

Some artists are beekeepers
No beekeepers are carpenters
*Therefore*, Some artists are not carpenters

Participants in syllogistic reasoning experiments are required either to produce their own logically valid conclusions from given premises, or to evaluate the validity of a presented conclusion (or conclusions) from given premises. It has been found that participants' responses in such experiments vary systematically according to three main factors. Two factors relate to the logical form of the syllogism and are termed *figure* and *mood*. Figure refers to the arrangement of the terms within the premises. There are four possible figures: A-B, B-C; A-B, C-B; B-A, C-B; and B-A, B-C (where A refers to the end-term in the first premise, C refers to the end-term in the second premise, and B refers to the middle term). Mood refers to the different combinations of logical quantifiers featured within the premises and conclusion. Four different quantifiers are used in standard English language syllogisms. These are commonly referred to by letters of the alphabet: A = *all*, E = *no*, I = *some*, and O = *some . . . are not*. The syllogism in the above example, therefore, can be said to be in the A-B, B-C figure, and in the IEO mood. Since there are four different figures and each of the two premises can feature one of four standard quantifiers, there or 64 standard syllogisms -- only 27 of these, however, yield valid conclusions. Studies have found that different combinations of figure and mood have a marked effect on reasoning performance. Indeed, some forms of syllogism are so easy that nearly all participants are able to give correct responses. Others are so difficult that few individuals respond without error (e.g., see Johnson-Laird & Bara, 1984; Johnson-Laird & Byrne, 1991).

In addition to the effects of figure and mood, participants' prior knowledge and beliefs have been found to bias responses. There are three basic findings that derive from studies of *belief bias* in syllogistic reasoning in which the validity of logical arguments has been manipulated alongside the prior believability of presented conclusions (see Garnham & Oakhill, 1994). First, believable conclusions such as "Some addictive things are not cigarettes" are more readily endorsed than unbelievable ones such as "Some millionaires are not rich people" (these examples are taken from Evans, Barston and Pollard, 1983). Second, logically valid conclusions are more readily endorsed than invalid ones. Third, there is an interaction between logic and belief such that the effects of believability are stronger on invalid problems than valid ones.

Few studies have directly attempted to investigate the processes underlying belief bias effects in syllogistic reasoning. One notable exception is the study carried out by Evans et al. (1983) who recorded and analysed the think-aloud protocols of participants evaluating the validity of believable and unbelievable presented conclusions. The majority of the protocols were classifiable under one of three headings: (a) *conclusion-only* protocols in which participants referred to a syllogism's conclusion without mentioning the premises; (b) *premises-to-conclusion* protocols in which participants referred to the premises of the syllogism and subsequently to the conclusion; and (c) *conclusion-to-premises* protocols in which participants referred to the conclusion and subsequently to the premises. A clear relationship was found between the type of protocol and the level of belief bias observed: belief bias was found to be strongest on problems where conclusion-only protocols were observed and weakest on problems where premises-to-conclusion protocols were observed. On this basis, the verbal protocols were taken to indicate distinct reasoning strategies (cf. Evans, Newstead & Byrne, 1993).

The analysis of concurrent verbal protocols is an established method in problem solving research (see Ericsson & Simon, 1993) and, to a lesser extent, in reasoning research (e.g., Beattie & Baron, 1988). There has, however, been a longstanding debate over the nature of concurrent verbal protocols and what they can reveal about cognitive processes and strategies. On the latter issue, Ericsson and Simon acknowledge that whilst many forms of verbalisations may not impact upon the *structure* of reasoning processes, such verbalisation may impact upon the *completeness* of the reports produced. This is because task-oriented processes will tend to have priority over verbalistion processes when such processes are in competition. As a consequence, participants may at times stop verbalising when the cognitive demands of the primary task are high, thus producing incomplete reports of the products of reasoning processes. Concerns over the completeness of verbal reports during reasoning encouraged us to explore an alternative process-tracing technique to investigate the processes underlying belief bias in syllogistic reasoning. The technique chosen was eye-movement analysis.

Eye-movement analysis is a technique that has been used extensively in reading research. Experimenters in this field assume a close association between patterns of eye movements and the thought processes underlying the understanding of written text (cf. Liversedge, Paterson & Pickering, 1998). That is, the position of a visual fixation is taken to indicate the piece of text that is currently being processed by the reader, and the length of a fixation or a gaze (which may include two or more fixations) is taken to indicate the ease with which a piece of text is processed. Similarly, the number of return fixations (or regressions) provides a further index of understanding (i.e., participants may need to return to an item of text in order to resolve ambiguities in meaning). The validity of a proposed association between thought processes and eye movements is supported by a large body of research which shows that the linguistic properties of text have a direct influence on readers' fixations and gazes (e.g., Rayner & Pollatsek, 1989).

Evidence from studies of reading would suggest that monitoring participants' eye movements whilst they are engaged in a text-based reasoning task could provide insights into the nature and organisation of the underlying processes associated with different types of syllogism. Indeed, eye-movement analysis may afford distinct advantages as a tracing technique over think aloud protocol analysis. Since eye movements are typically quite fast and spontaneous, an analysis of eye movements may provide more detailed records of the sequence and organisation of processing than think aloud protocols. Furthermore, since eye movements do not place additional processing demands on working memory in the manner that verbalisations might, working memory is left free for primary task-oriented processing, and eye movements associated with task-oriented processing should not cease when the processing demands of the primary task are high. Indeed, eye-movement investigations of reading would suggest quite the reverse, that is, when the processing demands of the primary task are high, lengthier fixations or a greater number of fixations upon the relevant text may be recorded.

The question remains, however, what can an analysis of participants' eye movements during a syllogistic reasoning task tell us about the cognitive processes underlying the task? This question can be addressed in the following way. Since working memory is the cognitive system within which many aspects of complex tasks such as deductive reasoning are carried out (cf. Gilhooly, 1998; Johnson-Laird & Byrne, 1991), and limited capacity and fragility of storage are key characteristics of this system, evidence from studies of reading would suggest that participants will need to read and re-read parts of the problem information which they are processing in order to construct, refresh or flesh out their mental representations when necessary. Thus, the high processing demands associated with some syllogisms may cause participants to gaze for longer upon elements of the problem information than with other less demanding problems. Evidence for the application of proposed heuristics which motivate reasoners to scrutinize the logical validity of some arguments more than others may also be detected in eye movements, such that longer gazes upon problem information may be evident with syllogisms where consideration is given to the logical argument than with other syllogisms where less logical scrutiny is applied. Based on these assumptions, predictions can be derived from contemporary theories of belief bias.

The mental models account of syllogistic reasoning (e.g., Johnson-Laird & Byrne, 1991) assumes that people begin reasoning by constructing a mental model in which a minimal amount of information concerning the logical relationships between the terms within the premises is made explicit. If a putative conclusion is true in this initial model, then it is tested against *fleshed out* models which make explicit more of the information within the premises. If a conclusion is found not to be consistent with a mental model, then it is rejected, otherwise it is accepted. Some syllogisms (termed *one-model* problems) are said to be relatively easy because they require the construction of a single mental model, and thus place a minimal load on working memory. Others are said to be more difficult because they place less manageable loads on working memory, requiring the construction of multiple models. The idea that the difficulty of syllogisms is closely associated with the number of models that need to be constructed has received strong support from empirical studies (e.g., Johnson-Laird & Bara, 1984; Bara, Bucciarelli, & Johnson-Laird, 1995).

The mental models account of belief bias (e.g., Oakhill & Johnson-Laird, 1985; Oakhill, Johnson-Laird & Garnham, 1989) assumes that prior beliefs determine whether participants will flesh out an initial model of the premises when testing the logical validity of a putative conclusion. Conclusions that are true in an initial model are accepted if they are believable, but tested against alternative and potentially falsifying models if they are unbelievable. In this way, the logic by belief interaction is explained. This account seems to predict that there will be an overall effect of belief on gazes, since greater consideration is given to the information within the premises when evaluating a conclusion that is unbelievable than one that is believable.

The mental models account assumes that two stages of mental models construction take place with syllogisms that lead to unbelievable conclusions: (a) a *pre-conclusion-gaze* stage, and (b) a *post-conclusion-gaze* stage. Only one stage of mental models construction, however, would occur with syllogisms leading to believable conclusions: a pre-conclusion-gaze stage. If two clear stages such as these can be identified from eye-movement analyses, then an interaction between reasoning stage (pre-conclusion / post-conclusion-gaze) and believability might be expected. This interaction would be such that the effect of belief upon gazes - whether measured in terms of duration or number of gazes would be greater in the post-conclusion-gaze stage than in the pre-conclusion-gaze stage.

Although much support has been claimed for the mental models account of belief bias, it has been criticised for failing to explain some key findings of belief bias research (e.g., Evans et al., 1993). For example, the account predicts that no logic by belief interaction should be observed with one-model syllogisms, since valid conclusions will be accepted and invalid conclusions rejected with such problems irrespective of their believability status. Although support for this prediction was found by Newstead et al. (1992), without ad hoc modifications (e.g., the addition of a *conclusion filter*) the account has difficulty in explaining the unpredicted finding of an effect of belief with one-model syllogisms (see Oakhill, et al., 1989).

In an attempt to explain belief bias findings, Quayle and Ball (1997) have proposed an account of belief bias based around the notion of *metacognitive uncertainty*. Set within the general framework of the mental models theory, this account assumes that the tendency to respond in accordance with belief is determined by the relative loads placed on limited working memory resources by different types of syllogism. In accordance with the mental models approach, it is assumed that some syllogisms place greater and less manageable loads on working memory than others, and that when working memory is overloaded participants are no longer able to test the truth of putative conclusions against models of the premises. In this instance, it is argued that being uncertain of a conclusion's logical status, participants fall back on a belief-based response as a *second-best* option.

The metacognitive uncertainty account's explanation of the logic by belief interaction hinges on the observation that with valid multiple-model syllogisms, correct responses can be given after the construction of a single mental model, whilst invalid multiple-model syllogisms require the consideration of more than one model (cf. Garnham, 1993; Hardman and Payne, 1995). In order to illustrate this idea, using Johnson-Laird & Byrne's (1991) notation the mental models that would be constructed for the syllogism given as an example earlier are shown below.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| a | [b] | | a | [b] | | a | [b] | |
| a | [b] | | a | [b] | | a | [b] | |
| | | [c] | a | | [c] | a | | [c] |
| | | [c] | | | [c] | a | | [c] |
| | ... | | | ... | | | ... | |

The As, Bs and Cs in each model represent the classes "artists", "beekeepers" and "carpenters" respectively. Each horizontal line represents the relationship between the three terms (the number of individual class members represented in each model is arbitrary). For example, the top two lines of the model on the far right show that there are As that are Bs that are not Cs, whilst the bottom two lines depict As that are not Bs but are Cs. The square brackets denote *exhaustive* representation. The class of Bs in each model is shown to be exhaustively represented in relation to the class of As -- that is, there can be no Bs that are not As. The three dots below each model indicate that there is premise information not yet made explicit in the model.

The valid conclusion to this three-model syllogism is "Some A are not C". As the second term in this conclusion (the C term) is represented exhaustively in relation to the B term in the initial mental model (on the far left), the relationship between the end terms in the model that shows the conclusion to be true (the top two lines) remains unchanged when the model is fleshed out. Hence, the consideration of more than one model is unnecessary. With valid problems, therefore, participants may feel certain of the correctness of their responses after the construction of a single model. Now let's consider the indeterminately invalid conclusion "Some C are not A". The bottom two lines of the initial model show this conclusion to be true. However, since the second term in the conclusion (the A term) is not represented exhaustively in this model, it is necessary to flesh out the model to be certain of the conclusion's logical status.

In the present study, and in earlier studies of belief bias that have employed a conclusion evaluation methodology, both the valid and the invalid problems that were used had determinate premises - that is, ones that yield a valid conclusion. So long as figure is kept constant, the use of such materials means that there should be little difference in the gaze behaviour between valid and invalid syllogisms prior to the point at which the conclusion is first gazed upon. However, the idea of a valid-invalid processing distinction suggests that after viewing the conclusion participants will be likely to gaze upon the premises for longer with invalid problems than with valid ones. For this reason, the metacognitive uncertainty account predicts that an interaction between reasoning stage (pre-conclusion-gaze/post-conclusion-gaze) and logic will be evident in participants' gazes.

The main aim of this study was to test the different eye-movement predictions made by the two theories described above, and in this way, to arbitrate between these accounts of belief bias. To this end, participants' eye movements were recorded using an eye-tracking device whilst they evaluated logical arguments whose presented conclusions varied in validity and prior believability.

## Method

### Participants

Twenty undergraduate psychology students at the University of Derby took part in the experiment. None of the participants had taken formal instruction in logic and all were tested individually.

### Materials

Whilst the participants carried out the reasoning task their eye movements were monitored using an ASL (Applied Science Laboratories) 4200R Eye Tracking System. This eye-tracking device operates on the 'Double Purkinje image' method. Measurements are taken of the relative changes in angle of infra-red light reflections from the front of the cornea and rear of the lens. This method allows for a degree of free head movement whilst monitoring is taking place (Megaw, 1990).

Two forms of three-model syllogism (e.g., as classified by Johnson-Laird and Byrne, 1991) were used. One form was valid and one form was invalid (i.e., the conclusions did not follow logically from the premises). Both the valid and invalid syllogisms were in the same A-B, B-C figure with conclusions of the form A-C. The valid problem was in the IEO mood, whilst the invalid problem was in the EIO mood. The invalid conclusions were *indeterminately* invalid (i.e., the conclusions were consistent with the premises but they were not *necessitated* by them).

A set of potential conclusions which were false by definition, (e.g., "Some kings are not men") was chosen, together with a set of believable conclusions, for example, "Some animals are not cats". The conclusions were devised so as to appear believable when the terms were presented in one order, but unbelievable when the terms were reversed. In order to assess believability, the potential conclusions were pre-rated by a group of 30 participants on a seven point scale ranging from -3 (*totally unbelievable*) to +3 (*totally believable*). Those conclusions which received the most extreme and consistent ratings were used in this study. Half of the valid and invalid syllogisms were presented with conclusions which were believable and half were presented with conclusions which were unbelievable by definition. In addition to the four types of three-model syllogism there were three one-model filler syllogisms which were used to distract the participants from the forms of the syllogisms of interest.

The syllogisms were presented individually on display cards in *times new roman* font size 36 (lower case = 6mm high, upper case = 8.5mm). The two premises were printed at the top of each card (the distance between the bottom of the letters in the first premise and the top of the lower case letters in the second premise was 23.5mm), and the conclusions were printed approximately two thirds of the way down the page (the distance between the bottom of the letters in the second premise and the top of the lower case letters in the conclusions was 112mm). The response words "yes" and "no" were printed on the left and right sides at the bottom of each page.

### Design

A within participants design was used, with all of the participants receiving the four three-model syllogisms together with the three filler syllogisms. These were preceded by 3 practice syllogisms (10 syllogisms in total). The order of the problem types was varied using a four by four balanced Latin square design; with the restriction that the filler items appeared in the same position in each booklet: in 2nd, 4th and 6th places. The thematic contents of the syllogisms were rotated over the different problem types, producing four different sets of materials. The four sets of materials were distributed evenly and randomly amongst the participants (i.e., five participants per set of materials). At the beginning of each booklet three practice syllogisms were given in order to familiarise the participants with the task. The participants were unaware that these were practice syllogisms.

### Procedure

Each participant was seated in a chair with a card display rack in front of them. The distance between the display rack and the participants' eyes was approximately 60cm. Once that the eye-tracking device had been calibrated, the following instructions were presented:

"This is an experiment to test people's reasoning ability. You will be given ten problems. You will be shown two statements and you are asked if certain conclusions (given below the statements) may be logically deduced from them. You should answer this question on the assumption that the two statements are, in fact, true. If, and only if, you judge that the conclusion necessarily follows from the statements, you should point to the word "yes", otherwise the word "no".

Please take your time and be sure that you have the right answer before giving your response. After you have given your response the next problem will be presented. Thank you very much for participating."

The 10 problem cards were placed in an upright pile upon the card display rack. After the participant had indicated their response to a syllogism (by pointing to either the "yes" or the "no") that problem card was removed to reveal the next problem card. The participants were allowed as much time as they required to complete the reasoning task.

A video camera mounted on the ceiling above and behind the participant recorded an image of each problem card as well as the participant's pointing responses. Horizontal and vertical eye movements were recorded using the infra-red tracking device. A small black square indicating eye movements was superimposed onto the video image by the tracking device. A digital timer (displaying hundredths of seconds) was also superimposed onto the bottom right hand corner of the video image.

## Results

### Conclusion Acceptances

An analysis of the conclusion-acceptance data revealed a significant effect of Belief, $p < .01$, one-tailed sign test, with participants accepting more believable conclusions than unbelievable conclusions (70% - 40% = 30%). The effect of Logic was in the standard direction, with more valid arguments accepted than invalid ones (63% 48% = 15%), but fell short significance. There was a significant interaction between Logic and Belief, $p < .01$, one-tailed sign test, such that the effect of belief was greater on syllogisms leading to invalid conclusions than on those leading to valid conclusions.

### Eye-movement Analysis

For the eye-movement analyses four fixation areas were identified: premises; conclusion; yes-no response words; and blank areas of display cards. The eye-movement video recordings were analysed frame by frame (since there were 25 frames per second, the shortest fixation that could be identified was 40 msec in duration) in order to establish the time duration of each gaze. A gaze typically included more than one separate fixation, and was defined as any time spent viewing a fixation area that was greater than 200 msec in duration. Gazes on the 'yes' and 'no' response words and blank areas of problem cards are not included in the following analyses. Due to refractive or pathological eye defects the eye-movement video recordings for three out of the 20 participants were uninterpretable. The recordings made for these participants have, therefore, been excluded from the following eye-movement analyses

In order to establish whether viewing the conclusion had an effect on subsequent premise gazes, the premise gaze times data for each type of syllogism were divided into pre-conclusion-viewing and post-conclusion-viewing times. These data were subjected to a multi-factorial analysis of variance. The factors were Stage (two levels: pre-conclusion-viewing / post-conclusion-viewing), Logic and Believability. None of the three factors was significant. However, Stage interacted with Logic, $F(1,16) = 5.06$, $p < .05$, such that with the invalid problems participants gazed upon the premises for a greater amount of time after viewing the conclusion than before. With the valid problem, however, this effect of stage was somewhat smaller and in the opposite direction. Other interactions were not significant.

## Discussion

This study assumed that the lengths of gazes identified from an analysis of participants' eye movements would provide some direct insight into the processes associated with the experimental manipulations of logical validity and believability. The finding of an effect of belief together with an interaction between logic and belief in the conclusion acceptances data provided a good opportunity to investigate the processes and strategies underlying these standard effects.

The mental models account claims that there will be two stages of mental models construction when multiple-model syllogisms are presented with *unbelievable* conclusions: a pre-conclusion-gaze stage in which participants construct an initial model of the premises; and a post-conclusion-gaze stage in which participants flesh out the initial model in a search for counter-examples which might show the conclusion to be false. On the other hand, when syllogisms are presented with *believable* conclusions the mental models account claims there will be only one stage of mental models construction: a pre-conclusion-gaze stage. The mental models account, therefore, appears to predict that there should be an interaction between stage (pre- / post-conclusion-gaze) and believability. No such interaction was evident in the data. The finding of an interaction between stage and logic, however, is consistent with the idea of a valid-invalid processing distinction that lies at the heart of the metacognitive uncertainty account. In the present study, and in earlier studies of belief bias that have employed a conclusion evaluation methodology, both the valid and the invalid problems used had determinate premises that is, ones that yield a valid conclusion. So long as figure is kept constant, the use of such materials means that there should be little difference in gaze behaviour between valid and invalid syllogisms prior to the point at which the conclusion is viewed. However, the idea of a valid-invalid processing distinction incorporated within the metacognitive uncertainty account suggests that after viewing a presented conclusion participants will gaze upon the premises for longer with invalid problems than with valid ones.

Whilst the pattern of eye-movement behaviour observed in the present study was predicted by the metacognitive uncertainty account, the conclusion-centred reasoning strategies identified from verbal protocol analysis by Evans et al. would predict quite a different pattern of eye movements. This observation supports the claim that think aloud protocols given during syllogistic reasoning tasks may be incomplete. We suspect that the processes involved in verbalisation may compete with task-oriented processing such that participants may stop verbalising at times when the processing demands of the primary reasoning task are high. Evans et al.'s identification of distinct reasoning strategies in studies of belief bias, therefore, may be a methodological artifact attributable to the employment of a think-aloud verbal protocol analysis methodology.

In conclusion, the study has demonstrated how an analysis of participants' eye-movements during reasoning can provide direct and detailed insights into the nature and time course of reasoning processes, which in turn can allow the researcher to arbitrate between conflicting accounts of reasoning phenomena. We maintain that the employment of eye-movement analysis in other reasoning paradigms alongside existing methodologies may enable researchers to gain a more detailed understanding of human deductive competence and performance than currently exists.

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