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Abstract

Two experiments are reported that tested core assumptions of the mental models theory of syllogistic inference (e.g., Johnson-Laird & Byrne, 1991) by examining inspection times for syllogistic components. Results supported mental models predictions of: (1) increased cognitive load across syllogistic figures, with differences in processing demand arising for BA-CB versus AB-BC problems for *both* conclusion-evaluation and conclusion-production tasks; and (2) conclusion-order preferences across figures – again in both the evaluation and the production paradigms. These findings challenge views of figural biases as being confined to conclusion-production tasks (Geurts, 2003; Rips, 1994) and theories that reject the assumption of figure-induced cognitive load (Chater & Oaksford, 1999). Since figural effects are typically viewed as being indicative of premise-driven processing, these results are also inconsistent with proposals that premise-driven processing prevails in conclusion-production, and conclusion-driven processing dominates in conclusion-evaluation (Morley, Evans, & Handley, 2004). The results also clarify the role of processing demands associated with conclusion validity: Valid conclusions were scrutinised less than invalid ones in the evaluation paradigm (as predicted by Hardman & Payne, 1995), supporting the notion that invalid syllogisms have at least two mental models. Although our specific results are not entirely consistent with recent models-based proposals, our basic findings remain broadly compatible with a models approach rather than alternative theoretical positions.

Keywords: Syllogistic reasoning; figural effects; processing direction; mental models; strategies; inspection times.

Introduction

Deduction and Mental Models

Deduction is the process by which we integrate information and infer what was previously implicit in such information. Studies of deduction have provoked fundamental debates concerning the functioning of the human mind and the extent and limits of human rationality (e.g., see Evans & Over, 1996). One of the dominant theories posited to account for deductive processes is that based upon the concept of mental models (e.g., Johnson-Laird & Byrne, 1991). According to this account, people achieve deduction through three processing stages. In the *comprehension* stage reasoners construct a model representing the information in the premises of a given argument. During the *description* stage they integrate the premises to formulate a putative conclusion. Finally, reasoners search for contradictory alternative models in the *validation* stage. Reasoners compare their putative conclusion with alternative models of the premises. If no counterexample model is found the putative conclusion is accepted as valid. The mental model theory of deduction has achieved substantial support from a variety of studies (for a review see Johnson-Laird, 2001). However, disputes in the literature question whether reasoning might be better understood in terms of a 'mental logic' (e.g., Braine, 1978; Rips, 1994), or as probabilistic Bayesian computations (e.g., Chater & Oaksford, 2001).

The main aim of the present paper is to test predictions derived from the mental models theory about the representation of premise information during deductive reasoning. The experiments test models-based predictions by using a technique that directly monitors the amount of *time* that processing effort is focused on premise and conclusion components of syllogisms. However, consideration is also given to the extent to which alternative theories of deduction can account for our data.

Syllogisms are a standard deductive reasoning task, and consist of two premise statements and a conclusion, each containing one of four logical quantifiers. These quantifiers determine the *mood* of a syllogism, and are referred to by letters of the alphabet, where A = *All*, E = *No*, I = *Some*, and O = *Some…are not*. The validity of a syllogism depends on the mood of the premises and conclusion and upon the order in which terms are arranged in the argument, that is, the syllogism's *figure*. In this paper we follow the convention (Johnson-Laird & Bara, 1984) of referring the three terms in a syllogism as A, B and C, where A is linked to B in the first premise, B to C in the second premise, and A to C in the conclusion. Thus, four figures can be defined as follows: AB-BC, BA-CB, AB-CB, and BA-BC.

Figural Effects

Research on syllogistic inference has demonstrated that a major influence on reasoning performance derives from the figure of presented arguments (e.g., Bara, Bucciarelli, & Johnson-Laird, 1995; Bara, Bucciarelli, & Lombardo, 2001; Dickstein, 1978; Ford, 1994; Johnson-Laird & Bara, 1984).

Figural effects have been extensively studied in syllogistic reasoning, however, there is evidence that the premise order plays a significant role in performance in other deduction paradigms (e.g., Garcia-Madruga, Moreno, Carriedo, Gutiérrez, & Johnson-Laird, 2001).

Johnson-Laird and Bara (1984) argued that figural effects occur when participants integrate premises. A figure where middle terms are contiguous (AB-BC) is less cognitively demanding than a figure where they are not (BA-CB). Based on Hunter (1957), Johnson-Laird and Bara (1984) proposed two mental manipulations to bring middle terms into contiguity: (1) reorder the representation of premises (BA-CB becomes CB-BA); or (2) switch around premise representations (*Some A are B* becomes *Some B are A*, however, *All A are B* does not switch around to be *All B are A*, but logically converts to *Some B are A*). Johnson-Laird and Bara (1984) also showed that participants preferred conclusions for figure AB-BC in the order A-C and for figure BA-CB in the order C-A. Broadbent's (1958) 'first-in first-out' (FIFO) rule combined with the mental manipulations outlined is used to explain these preferences.

Bara et al. (2001) developed a computational model (UNICORE) that assembles integrated mental models by overlapping matching middle terms in the two premises. This process is undemanding when the middle terms are contiguous, however, when the terms are not adjacent the cognitively demanding mental manipulations are invoked. Within this mental models theory, the FIFO property of working memory (WM) and the associated notion of cognitive demand are central in explaining the emergence of figural effects and conclusion-direction preferences.

Espino, Santamaria, and Garcia-Madruga (2000b) have proposed that the difficulty of syllogisms should be evident by increases in inspection times for the second premises of presented problems. They demonstrated support for this models-based prediction using a methodology whereby people's time spent processing second premises was examined. However, during the experiment participants were unable to refer to the first premise after viewing the second premise, thus creating an additional WM load. Gilhooly, Logie, and Wynn (2002) have argued that a WM load induced by the serial presentation of premises can inhibit the deployment of preferred reasoning strategies.

Some theorists have proposed that figural effects are restricted to conclusion-production paradigms (e.g., Geurts, 2003; Rips, 1994; Wetherick, 1989), whilst others dispute the notion that cognitive loads are induced by the figure of a syllogism (e.g., see Chater & Oaksford's, 1999, probability heuristics model – PHM). Mental models theory appears to be alone in its *explicit* argument for a WM load in reasoning induced by figure. Ford (1995) suggests an alternative explanation of figural effects to mental models, in the form of a verbal algebra, an explanation that does not directly specify WM involvement, but lends itself to an implicit assumption of WM load if reasoners cannot externalize their mental representations. Stenning and Yule (1997) proposed an explanation of figural bias that suggests the order of end terms in a conclusion is determined by the order of the terms in a 'source premise'. According to this theory, the source premise provides the so-called 'necessary individuals' whose existence is entailed by the premises. The source-founding hypothesis claims that the terms from the source premise will tend to precede the other end term in the conclusion and will also retain the order in which they appear in the source premise. However, it does not specify a cognitive load induced by figure.

Stenning (2002) is also critical of the mental models explanation of figural effects upon conclusion order. He suggests that it is insufficient merely to claim a role for the FIFO principle (Broadbent, 1958), but that further evidence is needed to support this explanation as such a mechanism is not necessitated by the representational system proposed. Stenning further argues that while the investigation of the order of terms in working memory is of psychological interest, evidence of this should not be claimed as supportive of any particular representational system. He suggests that any representational system could be modified to incorporate such effects. However, it remains that any theory failing to account for such evidence cannot be said to be a complete account of syllogistic reasoning performance. Accordingly, consistent evidence for a figural WM load in both evaluation and production tasks suggests that modifications may be needed for all of the leading theories of syllogistic reasoning - mental models theory apart.

Processing Direction

The figural effects outlined above tend to dominate syllogistic reasoning performance in the conclusion-production paradigm (Johnson-Laird & Bara, 1984), whereas figural effects are not well established in the conclusion-evaluation paradigm (Evans, Handley, Harper, & Johnson-Laird, 1999; Quayle & Ball, 2000). The standard models theory of syllogistic inference has tended to underplay the distinction between production and evaluation paradigms. Instead, the emphasis is upon the sequence of initial model construction, conclusion description and validation. Moreover, a theoretical debate concerning the direction of reasoning processes in the evaluation paradigm is developing (e.g., Morley et al., 2004), which concerns whether processing on evaluation tasks involves either: (1) 'forward reasoning' from the premises to the conclusion, as advocated in the standard models account and some of its recent variants (e.g., Bucciarelli & Johnson-Laird, 1999; Johnson-Laird & Byrne, 1991; Quayle & Ball, 2000); or (2) 'backward reasoning', whereby people use a presented conclusion to guide the construction of a model of the premises (e.g., Evans, Handley, & Harper, 2001; Hardman & Payne, 1995; Klauer, Musch, & Naumer, 2000). The backward-reasoning view is clearly a rather different proposal to the standard models claim that premise-driven processing underpins syllogistic inference.

Morley et al. (2004) argue that forward reasoning prevails in conclusion-generation tasks whereas backward reasoning prevails in conclusion-evaluation tasks. It is through this

distinction that they explain the lack of figural effects in conclusion-evaluation tasks. Backward-reasoning processes that use presented conclusions as initial models would be unlikely to show a cognitive demand induced by combining initial models with premises to form integrated models.

A further distinction can be drawn in the predictions of the standard mental models theory versus more recent variants of the theory in the context of the conclusion-evaluation paradigm. The standard theory assumes that participants need to construct all possible models of the premises to confirm the validity of the presented conclusion, whereas invalid conclusions require the discovery of only a single disconfirming model to enable its rejection. However, recent versions of models theory suggest that valid conclusions can be accepted as necessary without the exploration of falsifying models, while invalid conclusions require construction of a falsifying model to be refuted (Garnham, 1992; Hardman & Payne, 1995; Quayle & Ball, 2000). Others propose that only a single model is considered in either case (e.g., Klauer et al., 2000).

The experiments that we report here refined Espino et al.'s (2000b) inspection-time methodology by employing a more flexible problem-presentation technique, whereby clicking the mouse cursor on designated screen areas revealed a syllogism's first or second premise, or its conclusion. Once the cursor was removed from an active area this portion of the screen was instantly re-masked. This methodology reduces artifacts arising from the serial presentation of premises inhibiting participants' reasoning strategies (Gilhooly et al., 2002) because participants could refresh their mental representations of syllogistic components whenever they wished to.

Evaluation Task Predictions

According to the standard models theory, AB-BC figure syllogisms are easier to process than BA-CB ones, and should be associated with lower premise inspection times. However, backward-reasoning theories predict no such inspection-time imbalance across these figures. In addition, according to standard models theory, participants should prefer C-A conclusions for BA-CB syllogisms, whilst they should prefer A-C conclusions for AB-BC syllogisms. In line with such preferences it might also be expected that non-preferred conclusions would be associated with longer inspection times. Again, no such inspection time imbalance would be predicted by theories emphasising backward-reasoning processes. In relation to the validity status of conclusions it is possible to derive differential inspection-time predictions from variants of mental models theory. Some theories posit no difference in inspection times for valid over invalid conclusions because only one possible model of the premises is considered (e.g., Klauer et al., 2000). Contrasting theories (e.g., Quayle and Ball, 2000) predict lower inspection-times for valid conclusions because they only require the consideration of a single, initial model to be accepted, whereas invalid conclusions require further model construction to refute the fallacy.

Production Task Predictions

As there are no available conclusions that can guide a backward-reasoning process in the production paradigm then a forward-reasoning process (as espoused in the standard mental models theory) would be most likely to prevail. As such, the BA-CB figure would be predicted to have greater premise inspection times than the AB-BC figure. Participants would also be expected to produce more conclusions that are consistent with a figural bias than ones that are inconsistent with such a bias.

Experiment 1: Evaluation Paradigm

Method

Eight syllogisms were presented: four in the figure AB-BC, with the quantifiers IA, and four in the figure BA-CB with the quantifiers AI. Syllogisms were presented with a logically valid (I) conclusion or an invalid (O) conclusion. Valid and invalid conclusions were also presented either in figurally preferred or non-preferred orders (i.e., *Some A are C* vs. *Some C are A* conclusions for valid problems; *Some A are not C* and *Some C are not A* conclusions for invalid problems). The content of all syllogisms consisted of professions (e.g., Policemen), pastimes, and hobbies (e.g., Cyclists). Participants were asked to evaluate the logical validity of the presented syllogisms. The inspection time for each problem component formed the dependent variable. Authorware 5.1 was used to create displays and to collect data. Problems were presented with premises and conclusions masked. These components were revealed with a mouse pointer as participants evaluated the argument's logical validity. Forty-one undergraduates from the University of Derby participated in the experiment; none had been taught about reasoning or logic.

Results and Discussion

Premise Analysis Premise inspection times (see Table 1 for summary data) were positively skewed in all conditions, so a square-root transformation was conducted prior to inferential analysis. A 2 (Figure) by 2 (Quantifier) ANOVA revealed a main effect of Figure, $F(1, 40) = 18.2$, $p < .001$. Premises in the BA-CB figure were inspected significantly longer than those in the AB-BC figure, supporting the mental models argument for greater cognitive load when middle terms are not contiguous. This result was contrary to theories that do not predict an additional processing demand from figural effects (e.g., Chater & Oaksford, 1999). Premises with the quantifier 'Some' were scrutinised significantly longer than premises with the quantifier 'All', $F(1, 40) = 7.9$, $p < .01$, suggesting that quantifiers vary in representational complexity (cf. Anderson, 1981, who has argued that the 'Some' is a more demanding quantifier to represent than 'All'). There was also an interaction between Quantifier and Figure, $F(1, 40) = 7.2$, $p < .05$, which is consistent with a premise reordering strategy for the BA-CB figure that is moderated by quantifier complexity.

Table 1: Mean premise inspection times as a function of Figure and Quantifier.

	AB-BC		BA-CB		M	
	ND	TD	ND	TD	ND	TD
Some	5.75	5.33	5.99	5.68	5.87	5.51
All	4.50	4.32	6.19	5.85	5.34	5.09
M	5.13	4.83	6.10	5.76	5.61	5.30

Note. ND = natural data in seconds. TD = transformed data (square root of natural data) converted into original measurement units (seconds). Standard errors for the natural data ranged from 0.31 to 0.52, and from 0.07 to 0.10 for transformed data.

Conclusion Analysis Conclusion inspection times (Table 2) were also transformed to remove positive skew prior to ANOVA. The analysis revealed a reliable effect of Validity $F(1, 40) = 27.9$, $p < .001$. Valid conclusions were scrutinised less than invalid conclusions. This supports the proposal that valid syllogisms require the construction of only one model, whereas invalid conclusions require additional model construction to disconfirm the presented conclusion (Garnham, 1992; Hardman & Payne, 1995; Quayle & Ball, 2000). However, rules theorists such as Rips (1994) could argue that increased inspection time for invalid conclusions occurs because of the need to search for a proof that does not exist. There was also a reliable effect of Preferred Conclusion Order $F(1, 40) = 18.12$, $p < .001$. Participants inspected conclusions consistent with figural bias for less time than conclusions that were inconsistent with figural bias. The validity effects on conclusion inspection times are consistent with either forward- or backward-reasoning processes as described in recent variants of the mental models theory. However, the conclusion preference findings are more usually associated with theories that advance a forward-reasoning process. There was no significant interaction between Validity and Preferred Conclusion Order $F(1, 40) = 0.02$, $p > .05$.

Table 2: Mean conclusion inspection times as a function of Validity and Preferred Conclusion Order.

	Valid		Invalid		M	
	ND	TD	ND	TD	ND	TD
Preferred	2.99	2.89	4.09	3.88	3.54	3.37
Non-preferred	3.82	3.62	5.13	4.71	4.47	4.14
M	3.41	3.25	4.61	4.29	4.01	3.75

Note. ND = natural data in seconds. TD = transformed data (square root of natural data) converted into original measurement units (seconds). Standard errors for the natural data ranged from 0.17 to 0.52, and from 0.05 to 0.10 for transformed data.

Conclusion acceptance rates showed a significant effect of Validity, with more valid conclusions accepted (84%) than invalid conclusions (65%), $F(1, 40) = 22.7$, $p < .001$, providing evidence of participants distinguishing between I and O conclusions. There was a significant effect of Figure, $F(1, 40) = 6.1$, $p < .02$, such that more AB-BC syllogisms were accepted as valid (79%) than BA-CB (70%) ones. There was a trend toward a conclusion-order preference, $F(1, 40) = 2.6$, $p = .11$, with slightly more preferred conclusions accepted (76%) than non-preferred conclusions (72%).

Summary The results indicate a more salient role for figure in evaluation tasks than that suggested by many theorists (e.g., Geurts, 2003; Rips, 1994; Wetherick, 1989). The results are also incompatible with current mental models proposals (e.g., Morley et al., 2004) concerning the direction of cognitive processing arising in syllogistic inference. The observed effects of figure upon processing demand are not predicted by backward-reasoning theories that emphasise conclusion-driven processing, but are predicted by traditional forward-reasoning theories where people work from premises toward the presented conclusion (e.g., Bucciarelli & Johnson-Laird, 1999). The observation that invalid conclusions are inspected for longer than valid ones supports the proposal that valid conclusions require the construction of fewer models than invalid conclusions (e.g., Hardman and Payne, 1995; Quayle & Ball, 2000).

Experiment 2: Production Paradigm

Method

In the production-task experiment we presented participants with eight syllogisms: two in the AB-BC figure, with the quantifiers IA, and two in the BA-CB figure with the quantifiers AI. Distracter items were in the moods IE and EI. All procedural aspects of the experiment were the same as those in the previous evaluation study, with the exception that there were only two masked areas (corresponding to the premises) and a region where participants typed their responses to each pair of presented premises. Fifty-two University of Derby undergraduates participated in this study and none had been taught about reasoning or logic.

Results and Discussion

Premise Analysis The inspection-time data obtained in this study were positively skewed and were subjected to the same square-root transformation procedure as had been employed in Experiment 1 (see Table 3 for summary data). A 2 (Figure) by 2 (Quantifier) ANOVA revealed a significant main effect of Figure, $F(1, 51) = 18.9$, $p < .001$, with premises in the figure BA-CB being inspected significantly longer than premises in the AB-BC figure. Premises with the quantifier 'Some' were scrutinised longer than premises with the quantifier 'All' $F(1, 51) = 10.5$, $p < .001$, again supporting the idea that 'Some' is a more demanding quantifier to represent than 'All'.

Table 3: Mean premise inspection times as a function of Figure and Quantifier.

	AB-BC		BA-CB		M	
	ND	TD	ND	TD	ND	TD
Some	9.85	8.78	15.19	13.29	12.52	11.03
All	7.03	6.59	14.14	12.35	10.59	9.47
M	8.44	7.68	14.67	12.82	11.55	10.25

Note. ND = natural data in seconds. TD = transformed data (square root of natural data) converted into original measurement units (seconds). Standard errors for the natural data ranged from 0.51 to 1.80, and from 0.09 to 0.19 for transformed data.

Conclusion Analysis There were no significant differences between figures for the quantifiers produced, $\chi^2(4) = 5.4$, $p > .05$, and 79% of responses were valid (i.e., 'Some… are…' conclusions). There was a highly significant association between the preferred conclusion direction and participants' responses, $\chi^2(2) = 138.2$, $p < .001$, with 72% of responses being in the preferred direction. However, this association was stronger for the figure AB-BC (82%) than BA-CB (63%), $\chi^2(2) = 10.5$, $p < .01$. This supports the FIFO property of working memory, whilst also suggesting possible individual differences in mental manipulations when they do occur. These conclusion-direction findings are consistent with a 'forward reasoning' process as advanced in standard mental models theory.

General Discussion

Our experiments aimed to test central predictions of the mental models theory of syllogistic reasoning. These predictions concerned the way in which the figure of presented problems should impact upon the processing effort required to formulate models of given premises and to establish the logical validity of conclusions. We set out to test such predictions using a computer-based, inspection-time methodology similar to that pioneered by Espino et al. (2000b). However, Espino et al.'s (2000b) study, prevented participants from referring back to the first premise of a problem once the second premise had been revealed, and thus restricted the detection of the precise locus of figural effects on processing, and did not allow for a conclusion-centered backward-reasoning process - as proposed in recent accounts of evaluation-task performance (e.g., Evans et al., 2001; Hardman & Payne, 1995; Klauer et al., 2000).

The two experiments presented provide evidence that generally concurs with the standard mental models theory of syllogistic inference (e.g., Bara et al., 2001; Johnson-Laird & Bara, 1984). This is the only contemporary account that explicitly posits a WM demand arising from syllogistic figure. Our experiments support the notion of a cognitive load that is induced by reasoning with syllogisms that have non-contiguous middle terms for both conclusion production and evaluation tasks. This evidence replicates findings from Espino et al. (2000b) whilst using different syllogisms and a methodology that allows for more flexible strategy deployment than in their study. The findings also broadly replicate the results of a process tracing experiment by Stupple and Ball (2005) that found similar effects of figure, validity and conclusion preference using multiple-model syllogisms with a conclusion-evaluation paradigm.

The consistency of findings across both evaluation and production formats is contrary to theories that suggest figural effects are a quirk of production tasks (e.g., Geurts, 2003; Rips, 1994; Wetherick, 1989). Although Chater and Oaksford's (1999) model is able to predict the most frequently endorsed and generated conclusions in both experiments, as well as the observed tendency for 'Min' premises to be viewed consistently longer, their account predicts no figurally-induced cognitive load in syllogistic reasoning. In response to Espino et al.'s (2000a) experiment that claimed evidence for figural effects based on the activation of end-terms in memory, Oaksford argued that: "Their [Espino et al.'s] finding does not address the issue of processing difficulty, so it is difficult to see how it bears on PHM's prediction of no differences in processing difficulty between figures" (Oaksford, 2001, p. 208). So, whilst Oaksford disputes the validity of Espino et al.'s (2000a) measure, he indicates that if a measure of processing difficulty demonstrated a difference between figures this would challenge the current formulation of the PHM.

Although the figure-induced load is inconsistent with several contemporary theories, we agree with Stenning (2002) that this does not provide fundamental evidence against the core principles of those theories, as it is quite possible to modify a heuristics-driven or rules-based theory to incorporate a component specifying a cognitive load induced by the non-contiguity of middle terms. One possible avenue would be through a mental algebra akin to that proposed by Ford (1994). However, it is suggested that until these theories develop an explicit account of how figure impacts upon WM they remain less complete than mental models theory as an explanation of syllogistic inference.

The evidence we present for figural influences on premise and conclusion processing are also not entirely in accordance with all current model-based theories. For example, a figural influence in an evaluation paradigm calls into question proposals from Morley et al. (2004) for a dissociation between the reasoning strategies employed in conclusion-evaluation compared with conclusion-production tasks. They propose that forward reasoning may dominate in the conclusion-production paradigm, whereas backward reasoning may prevail in the conclusion-evaluation paradigm as presented conclusions can motivate the construction of models incorporating those conclusions. Our evidence for figural effects on processing for evaluation tasks and their similarity to the patterns of inspection-times for production tasks is not easily reconciled with Morley et al.'s position. It is possible, however, that Morley et al.'s use of belief-oriented materials might explain the strategic

differences observed across studies (see also Ball, Phillips, Wade, & Quayle, in press, for evidence supporting conclusion-driven processing in a belief-bias paradigm).

The standard mental models theory also failed to account for our full range of findings. The longer inspection time for invalid conclusions relative to valid ones was inconsistent with the proposal that there would be no difference between them because there is only one possible model of the premises that we employed. This validity effect instead supports the view that valid conclusions can be accepted as necessary without the exploration of falsifying models, while invalid conclusions require construction of a falsifying model to be refuted (e.g., Garnham, 1992; Hardman & Payne, 1995; Quayle & Ball, 2000). An alternative explanation may be that the invalid conclusions are more difficult to represent due to the more complex 'O' quantifier (Anderson, 1981). However, Stupple and Ball (2005) have recently shown a similar difference, when all evaluated conclusions have the 'O' quantifier.

In summary, it would appear that current theories of syllogistic reasoning do not simultaneously accommodate evidence for: (1) processing imbalances across the premises of different figures - as reflected in differential premise inspection times in both evaluation and production paradigms; and (2) the effects of validity and preferred conclusion direction observed in the conclusion components for evaluation tasks. Although most key theories of syllogistic reasoning might be able to extrapolate their central principles to account for figural influences on premise and conclusion processing, it remains for the proponents of these theories to take up this challenge.

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