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Multiple layers of information processing in deductive reasoning: combining dual strategy and dual-source approaches to reasoning

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ABSTRACT

The idea that inferential performance cannot be analyzed within a single model has been suggested within two theoretical contexts. The dual strategy model suggests that people reason using different approaches to processing statistical information. The dual-source model suggests that people reason probabilistically using both statistical information and some intuition about logical form. Each model suggests that people have different approaches to processing information while making inferences. The following studies examined whether these different forms of information processing were equally present during reasoning. Participants were given a series of problems designed to distinguish counterexample from statistical reasoners. They were then given a series of MP or AC inferences for which identical statistical information was provided. Results show that MP inferences were considered to be deductively valid more often than equivalent AC inferences. The effect of logical form was independent of reasoning strategy, and of relatively equivalent size for both counterexample and statistical reasoners. The second study examined explicitly probabilistic inferences, and showed smaller effects of logical form and of reasoning strategy, although with a complex set of interactions. These results show that understanding the way that people use information when making inferences requires a multidimensional approach.

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Reasoning; dual strategy; dual source; conditional reasoning

The ability to make deductive inferences is one of the most advanced forms of logical reasoning. Although much research has shown that the "logical" inferences that even educated adults make are highly variable, it remains that logical reasoning is a critical component of advanced mathematics and science. Accordingly, understanding how people make such inferences remains an important question. Often this question is cast within the context of ongoing debates between theories, such as mental model (Johnson-Laird & Byrne, 1991, 2002) or probabilistic theories (Evans & Over, 2004; Oaksford & Chater, 2003). There is a tendency for theories to claim to provide a single underlying model for the way that people make deductive inferences. While this is a matter of debate, there is strong evidence that people actually have quite complex ways of approaching deductive problems. More specifically, whatever the different processes involved, deductive inferences appear to be made using a variety of informational cues. For example, recent studies have provided strong empirical support for a dual strategy model of deductive inference (Markovits, Brisson, & de Chantal, 2015; Markovits, Brunet, Thompson, & Brisson, 2013; Markovits, Forgues, & Brunet, 2012; Verschueren, Schaeken, & d'Ydewalle, 2005a, 2005b). This model suggests that one of the major distinctions in the way that people make such inferences is the way that statistical information – which is either explicitly or implicitly presented through premise content – is processed. The importance of such statistical information is supported by the many studies have shown that the inferences that people make for what are identical forms of inferences depend nonetheless on the specific content of the premises (Cummins, 1995; Cummins, Lubart, Alksnis, & Rist, 1991; Markovits, 1984; Markovits & Vachon, 1990; Thompson, 1994, 1995). These studies suggest that when people reason with familiar premises, they will activate knowledge about the premises (Quinn & Markovits, 1998), which includes activation of

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networks of alternative antecedents and/or disabling conditions. This information, among other things, allows some statistical estimation of the probability that a given conclusion will be true, given the premises. There are indeed different theoretical models attempted to explain such content effects, including mental model theory (Johnson-Laird & Byrne, 2002). Consistent with these different approaches, the dual strategy model postulates that people can use this information in two different ways. A statistical strategy translates such information directly into a subjective likelihood of a putative conclusion. A counterexample strategy examines this information base for the presence or absence of potential counterexamples to a conclusion. It should be noted that such a strategy is consistent with a variety of different theoretical approaches. It is initially derived from mental model theory, since counterexample generation is a key part of this theory. However, the concept of *p*-validity (Evans, Thompson, & Over, 2015; Singmann, Klauer, & Over, 2014) would generate the same pattern of inferences on the diagnostic problems as the one that characterises the counterexample strategy. The *p*-validity model is in many respects isomorphic to the mental model description of the counterexample strategy. Nonetheless, the dual strategy model postulates an important qualitative difference in the way that people process statistical information about premises, one that is independent of logical competence (Markovits, Brisson, & de Chantal, 2016). Importantly, people can change strategies in response to such factors as time constraints (Markovits et al., 2013) and the way that problems are presented (Markovits, Lortie Forgues, & Brunet, 2010).

It should be noted that the dual strategy model is certainly related to the more general dual process models that have been postulated as a general explanatory mechanism that can account for the tendency of people to make judgments based on non-logical factors such as belief in the conclusion (Evans, Barston, & Pollard, 1983. Dual process models suggest the existence of two separate inferential systems, often referred to as Type I which is more intuitive reflects belief and Type 2 which is more working memory intensive and at least potentially more "logical" (Evans, 2007; Stanovich & West, 2000; Sloman, 1996), see (Evans & Stanovich, 2013) for a recent review. In this perspective, the statistical strategy would be an instantiation of a Type 1 process, while the counterexample strategy would be an instantiation of a Type 2 process. Dual process models generally assume that use of Type 1 processes is fairly automatic and not under conscious control. However, there is evidence that statistical strategy use, as defined by the dual strategy model, is under some degree of metacognitive control (Markovits et al., 2013; Markovits, Brisson, de Chantal, & Thompson, 2017), and that use of a counterexample strategy can lead to less logical reasoning in certain circumstances (Markovits et al., 2016). On the other hand, recent evidence is consistent with a dual process interpretation of the dual strategy model (Markovits, Trémolière, & Blanchette, in press). Thus, while the basic distinction in the way that information is processed that is the basis of the dual strategy model has been clearly validated by several studies, the extent to which this can be seen as a dual process model remains an open question.

Another line of research that points towards the additional complexity of inferential behaviour is the recent dual-source model of probabilistic inferences (Klauer, Beller, & Hutter, 2010; Singmann et al., 2014; Singmann, Klauer, & Beller, 2016). This model suggests that when people make probabilistic inferences, they are susceptible to both statistical information, which is the most direct form of information available to make such inferences, and critically to the logical form of the inferences. The latter is the result of previous experience with reasoning and represents the perceived validity or subjective degree to which an inference form is seen as logically warranted (e.g. for most individuals MP has a greater perceived validity than AC). Inferences are considered to represent a mixture of these two sources of information. With the exception of a reanalysis of the data from Markovits et al. (2015; see Singmann et al., in 2016) this model has not been directly applied to inferences with respect to deductive validity, but there is a clear connection to the dual strategy model. This analysis indeed suggests that deductive inferences are influenced both by content and by logical form, although the differentiation between the two is necessarily indirect. In the dual strategy model, both statistical and counterexample strategies are different ways to process statistical information. Now, one of the key differences between the two strategies is observed when statistical information generates a high likelihood of a given conclusion, but nonetheless presents possible counterexamples (Markovits et al., 2013; Markovits et al., 2016). The model predicts (and has shown) that more statistical reasoners will consider that these conclusions are valid than will counterexample reasoners, with the difference between the two strategies disappearing as the likelihood decreases. If the dual source model is correct, then it would be predicted that this basic effect would be modulated by logical form. The aim of the present study is to test this interplay of dual strategy and dual-source model and, more specifically, to test the prediction of the dual-source model that, given the same statistical information, logical form should nevertheless influence the inferences drawn.

Study 1

In order to do so, we adapted a method used in previous studies examining the dual strategy model (Markovits, Brisson, & de Chantal, 2016). We presented reasoners with inferential problems for which explicit statistical information regarding the empirical probability of a putative conclusion being true was provided. We also presented reasoners with one of two different inferential forms, one of which corresponded to the Modus ponens inference (P implies Q, P is true) while the other corresponded to the Affirmation of the consequent inference (P implies Q, Q is true). Critically, the statistical information provided is identical for both inferential forms. We hypothesised that inferential performance would vary both according to strategy and according to logical form. More specifically, since modus ponens inferences are more often considered to be valid than affirmation of the consequent inferences (i.e. MP should have a higher perceived correctness or higher τ parameter in the dual-source model notation than AC), we hypothesised that the overall rate of acceptance of the former would be greater than the rate of acceptance of the latter.

We examined the effects of logical form on acceptance rates of MP and AC inferences in the context of explicit statistical information that modifies the relative strength of the relationship between antecedent and consequent terms. In order to do this, we present a series of identical inferences. For each, after presentation of the conditional rule, participants receive the results of 1000 observations which present the number of times that the consequent is true and the number of times that it is false when the antecedent is true. There were four categories which were defined by the relative numbers of cases in which the antecedent was true and the consequent was also true, these were 100%, 99%, 75%, and 50%. However, note that there were small variations in the exact numbers used. Previous results have shown that such frequency information will be processed in qualitatively different ways by counterexample and by statistical reasoners (e.g. Markovits et al., 2015). A statistical reasoner will translate this relative frequency (which we will refer to as *relative strength*) into the perceived likelihood of the MP conclusion being true. This should lead to acceptance rates of this conclusion that are directly related to relative strength (i.e. the stronger the relationship the higher the acceptance rates). By contrast, counterexample reasoners should consider such information as indicating the existence of potential counterexamples to conclusions, which should lead to generally lower rates of acceptance of the MP conclusion, since even very high relative strength indicates the possibility of a potential counterexample. Importantly, we hypothesise that the effect of strategy will be independent of logical form, so that while the relationship between strategy and inferential behaviour will follow the same pattern, overall both statistical and counterexample reasoners will accept MP inferences more often than AC inferences.

We also presented participants with a series of DA inferences also with explicit statistical information that were used as a strategy diagnostic. This was identical to those used in previous studies, with the difference that DA (P implies Q, P is false) instead of AC inferences were used. There were two series of such inferences, one of which presented information suggesting that the invited inference was very improbable (50%), while the second suggested that the invited inference was highly probable (99%), with explicit counterexamples. DA inferences were used in the diagnostic problems to differentiate these from the inferences used to examine the effect of relative strength.

Method

Participants

A total of 158 University students (64 males, 94 females: average age = 24 years, 7 months) took part in this experiment. Students were native French speakers at the Université du Québec à Montréal and all were volunteers.

Material

Four paper and pencil booklets were prepared. On the first page of each booklet, participants were asked to give basic demographic information. Following this, they were given the following instructions (translated from the original French):

> Imagine that a team of scientists are on an expedition on a recently discovered planet called Kronus. On the following pages, we will ask you to answer questions about phenomena that are particular to this planet. For each problem, you will be given a rule of the form "if … then … " that is true on Kronus according to the scientists. It is very important that you suppose that each rule that is presented is always true. You will then be given additional information and a conclusion that you must evaluate.

In the first booklet, participants were given two series of inferences, the first of which presented *Relative Strength* MP inferences, while the second series presented the *Strategy Assessment* problems.

Relative Strength MP Inferences were presented in the following way. At the beginning of each problem, a causal conditional rule containing a nonsense term followed by a series of observations and an MP inference was presented. The observations provided an estimate of the probability that the suggested conclusion was empirically true, i.e. the relative strength of the inference. These problems were presented in the following format:

> A team of botanists observed trees on Kronus and noted an interesting phenomenon. The scientists noted that on Kronus:
>
> If it bruidonnes then the trees become red.
>
> Of the last 1000 times that it bruidonned, the scientists made the following observations:
>
> 990 times it has bruidonned and the trees became red.
>
> 10 times it has bruidonned and the trees did not become red.
>
> Based on these informations, Jean reasoned in the following way:
>
> The scientists affirm that: If it bruidonnes then the trees become red.
>
> Observation: It bruidonnes.
>
> Conclusion: The trees will become red.
>
> Indicate whether or not this conclusion can be drawn logically from the statements.

Participants were given a choice between a NO and a YES response.

This problem thus presented observations with a Relative Strength of 99.0%. There were 11 subsequent inferences using the same format, but each with a different conditional rule and followed by a set of observations that corresponded to different Relative Strengths. These were, in order: 75.0%, 100%, 51.0%, 50.5%, 74.5%, 100%, 99.2%, 98.7%, 76.0%, 100%, 49.0%. There were 3 inferences for each of the general Relative Strength categories: 100%, 99%, 75%, and 50%. Problems were presented two to a page.

The *Strategy Assessment* problems were a variant of the set of 13 problems used by Markovits et al. (2012). Each problem described a causal conditional relation involving a nonsense term and relations followed by a Denial of the antecedent inference. Each problem also included frequency information concerning the relative numbers of "not-P and not-Q" and "not-P and Q" cases out of 1000 observations. For each problem, participants were given a putative conclusion and asked to make a dichotomous judgement of validity (yes, no).

Of the 13 items, 5 had a relative strength that was close to 90% (each individual item varied between 92% and 90%), 5 had a relative strength that was close to 50% (each individual item varied between 48% and 50%), and 3 had a relative strength of 100% (these last were presented in order to provide greater variability in problem types). The following is an example of the 90% condition:

> A team of geologists on Kronus have discovered a variety of stone that is very interesting, called a Trolyte. They affirm that on Kronus, if a Trolyte is heated, then it will give off Philoben gas.
>
> Of the 1000 last times that they have observed Trolytes, the geologists made the following observations:
>
> 910 times a Trolyte was not heated, and Philoben gas was not given off.
>
> 90 times a Trolyte was not heated, and Philoben gas was given off.
>
> From this information, Jean reasoned in the following manner:
>
> The geologists have affirmed that: If a Trolyte is heated, then it will give off Philoben gas.
>
> Observation: A Trolyte is not heated.
>
> Conclusion: The Trolyte will not give off Philoben gas.

An initial booklet was constructed which presented the *Relative Strength* MP inferences first followed by the *Strategy Assessment* problems. A second booklet was constructed which was identical to the first except that the *Strategy Assessment* problems were presented first followed by the *Relative Strength* MP inferences.

Two other booklets were constructed which were identical to the initial two with one exception. The relative strength MP inferences were replaced with *Relative Strength AC inferences*. These comprised a series of AC inferences for which explicit statistical information was presented which corresponded to the relative probability that the AC inference was empirically true, with parameters identical to the relative strength MP inferences. The following is an example of such an inference:

> A team of botanists observed trees on Kronus and noted an interesting phenomenon. The scientists noted that on Kronus:
>
> If it bruidonnes then the trees become red.
>
> Of the last 1000 times that the trees became red, the scientists made the following observations:
>
> 990 times it has bruidonned and the trees became red.
>
> 10 times it has not bruidonned and the trees became red.
>
> Based on this information, Jean reasoned in the following way:
>
> The scientists affirm that: If it bruidonnes then the trees become red.
>
> Observation: The trees became red.
>
> Conclusion: It has bruidonned.
>
> Indicate whether or not this conclusion can be drawn logically from the statements

Participants were given a choice between a NO and a YES response.

There were thus a total of four booklets. Half of the booklets used the relative strength MP problems while the other half used the relative strength AC problems.

Before proceeding, it is worth examining the way that the Strategy assessment problems and the Relative strength problems are structured, and analyzed. Both sets of problems present series of identical inferences accompanied by explicit statistical information that corresponds to the empirical probability of the suggested conclusion being true. The key problems in the strategy assessment consisted of 5 DA inferences with relative strengths of about 90% and 5 DA inference with relative strengths of about 50%. Since both of these sets suggest the presence of potential counterexamples to the DA inference, a reasoner following a consistent counterexample strategy would reject all of them. A reasoner using a statistical strategy would use this statistical information to generate a likelihood of the conclusion being true, which would lead to a greater number of acceptances for the 90% items than for the 50% items. The key criteria here is thus the relation between the 90% and the 50% items. It should be noted that previous studies have used sequences of AC inferences for the Strategy assessment procedure, but here we decided to use DA inferences since one of the key problems used to examine the relative effects of logical form involved AC inferences.

The relative strength MP (and AC) problems present a variety of strengths (100%, 99%, 75% and 50%). The key metric for analyzing these is the total number of accepted inferences, with relative strength included as a modulator for which there is no specific hypothesis.

Procedure

Booklets were randomly distributed to entire classes. Students who wished to participate were told to take as much time as they needed to answer the questions.

Statistical analysis

Given the binary nature of the dependent variable, our data could not reasonably be described as following a normal distribution. Consequently, an analysis via ANOVA was not appropriate. Instead, we employed a binomial generalised linear mixed model (GLMM; e.g. Jaeger, 2008). Such a model, which is essentially a repeated-measures logistic regression, adequately accounts for the binary nature of the dependent variables and handles the repeated-measures nature of the Relative strength factor. Following Barr, Levy, Scheepers, and Tily (2013), we first estimated models with the maximal random-effects structure justified by the design (i.e. by-participant random intercepts and random slopes for Relative strength). However, the maximal models did not convergence successfully and we had to remove the random slopes. Consequently, the following results are based on models with random intercepts only. To test the significance of fixed-effects we used likelihood-ratio tests as implemented in package afex (Singmann, Bolker, Westfall, & Aust, 2017).

Results and discussion

We first compared performance on the MP and the AC problems for the relative strength problems. We estimated a binomial GLMM with the binary acceptance ratings to the inferences as dependent variable, with fixed-effects for Relative strength (100%, 99%, 75%, 50%; as a categorical variable), Logical form, Order, as well as their interactions. This GLMM showed no effect of Order (largest $\chi^2(1) = 1.57$, smallest $p = .67$). However, this GLMM showed a significant main effect of Logical form, $\chi^2(1) = 9.23$, $p = .002$, indicating that inferences were accepted more frequently for the MP problems than for the AC problems. It also showed a significant main effect of relative strength, $\chi^2(3) = 814.15$, $p < .0001$;, indicating that the number of accepted inferences decreased with decreasing Relative Strength. Additionally, it showed a significant logical form × relative strength interaction, $\chi^2(1) = 16.02$, $p = .001$, displayed in Figure 1. Consequently, we investigated this interaction using follow-up tests, controlling the error rate using the Bonferroni–Holm method. This analysis showed that the MP inferences were accepted more strongly than AC inferences for the 100% (MP: Mean acceptance rate (*M*) = 98%: AC: *M* = 78%) and the 99% (MP: *M* = 67%: AC: *M* = 31%) problems. The difference between the two forms was not significant for the 75% (MP: *M* = 22%, AC: *M* = 10%) and the 50% (MP: *M* = 2%, AC: *M* = 2%) problems.

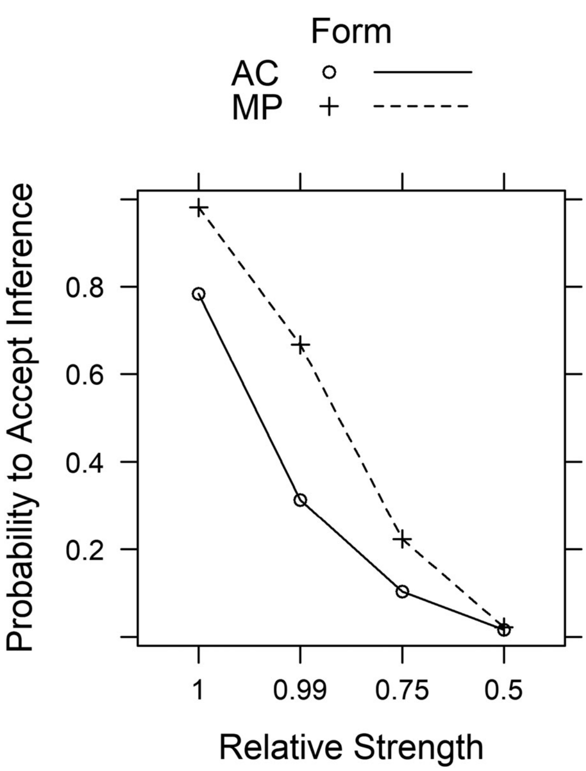

Figure 1. Estimated acceptance rates to the inferences in Study 1 as a function of logical form and statistical information.

We then analysed performance on the *Strategy Assessment* problem set. Participants who rejected all of the 90% inferences and all of the 50% inferences were put into the *Counterexample* category. Participants for whom acceptance rates were greater on the 90% items than that on the 50% items were put into the *Statistical* category. A total of 28 participants (18%) were not grouped into one of these two categories (these responses for which acceptance rates were greater on the 50% then on the 90% items and responses with equal numbers of acceptances on the 50% on the 90% items where at least one of each was accepted), and these were eliminated from subsequent analyses. It should be noted that previous studies have found between 20% and 30% of participants could not be classed in either of these two categories, with roughly even splits between numbers of participants in the two categories.

We then estimated a second GLMM on the acceptance rates for the MP and the AC inferences with fixed-effects for Relative Strength (100%, 99%, 75%, 50%), Strategy (Statistical, Counterexample), Logical form (MP, AC) and Order (Assessment first, Relative strength first), as well as all interactions. However, this model did not converge successfully. Consequently, we refitted it without including any effects of Order, as Order did not show any effect in the analysis excluding Strategy. This GLMM showed a significant main effect of Strategy, $\chi^2(1) = 51.77$, $p < .0001$;, a main effect of Relative Strength, $\chi^2(3) = 844.74$, $p < .0001$;, as well as a Relative Strength × Strategy interaction, $\chi^2(3) = 69.82$, $p < .0001$;. We did not find a main effect of Form, $\chi^2(1) = 0.0$, $p > .99$, nor any interaction involving Form, largest $\chi^2(3) = 6.56$, smallest $p = .09$. The absence of the main effect of Form appeared to be a consequence of the nonlinear logistic transformation as it clearly reappeared in a further GLMM from which we excluded Relative Strength, $\chi^2(1) = 9.09,\ p = .003$ (this model also showed an effect of Strategy, $\chi^2(1) = 67.69,\ p < .0001$, but also no Form × Strategy interaction, $\chi^2(1) = 1.11,\ p < .29$).

The three-way interaction of Strategy, Relative Strength, and Form is displayed in Figure 2. The pattern underlying the strategy and relative strength interaction essentially replicated previous findings (Markovits et al., 2015). Specifically, reasoners tending to use a counterexample strategy showed significantly lower rates of acceptance of the inferences (combined over the MP and the AC forms) than reasoners using a statistical strategy. This difference was significant for the 99% and the 75% items, but not for the 100% and 50% items (again controlling the error rate using the Bonferroni–Holm method). As can be seen from Figure 2, for counterexample reasoners there was a significant drop in the number of accepted inferences between the 100% and the 99% items, while for statistical reasoners this difference was not significant. In other words, the simple presence of a minimal number of potential counterexamples has a very strong influence on counterexample reasoners while having almost no influence on statistical reasoners. This difference appears to be attenuated when conclusion likelihood is low (i.e. when comparing the pattern of MP versus that of AC). However, as Form did not interact with Strategy, we refrain from interpreting this in more detail.

The results of this study allow two clear conclusions. First, they show that inferences about deductive validity for which statistical information is identical are clearly influenced by logical form. This is, to our knowledge, the first direct evidence of this prediction of the dual-source model (Klauer et al., 2010; Singmann et al., 2016). Thus, we also extended the scope of the dual-source model, applying it not only to explicitly probabilistic inferences but to inferences of deductive validity. The second result shows that the effect of logical form and that of the reasoning strategies postulated by the dual strategy model are separable.

Study 2

The results of Study 1 show that when given premises with explicit statistical information related to the probability of a putative conclusion being true, both counterexample and statistical reasoners judge that MP inferences are valid more often than AC inferences. This method allows equating associated statistical information in a way that presenting premises with familiar content, and with correspondingly implicit information, would not allow. However, as we have shown in a previous study (Markovits et al., 2015), judgments of validity are more complex and more prone to variability than are explicitly probabilistic inferences. This is at least partly because making judgments of validity requires transforming statistical information into a dichotomous judgment. Such a transformation implicitly requires using some internal criteria in order to translate varying levels of probability into a single judgment (valid or not). There are two reasons that this process would make the influence of logical form per se generally stronger. On the one hand, it is possible that the criteria used might itself vary by form (for example, a 70% conclusion might be judged as valid for an AC inference, but not for a MP inference). It is also possible that the simple fact of transforming probability into validity judgments might generate additional attention to the form of an inference. By contrast, when explicit statistical information accompanies inferential problems, this information should allow a fairly direct likelihood evaluation, in the absence of any requirement to transform statistical information into a different modality.

From the perspective of the dual-source model, we also predict differences in the impact of logical form on responses from deductive versus probabilistic inferences. When considering the previous application of the dual-source model to deductive inferences (i.e. the reanalysis of Markovits et al., 2015; reported in Singmann et al., 2016) statistical information (i.e. background knowledge in dual-source terminology) enters the formula predicting the responses once for deductive inferences but twice for probabilistic inferences (compare Equation (9) with Equation (6) in Singmann et al., 2016). This entails that the relative effect of form-based information is stronger in deductive inferences. Furthermore, one of the predictions of the dual-source model – confirmed, for example, in the reanalysis of the Markovits et al. data – is that the weighting of the form-based component is stronger for deductive inferences than probabilistic inferences. This also entails that differences in the perceived correctness between different inference forms (such as MP versus AC) should be more pronounced for deductive compared to probabilistic inferences.

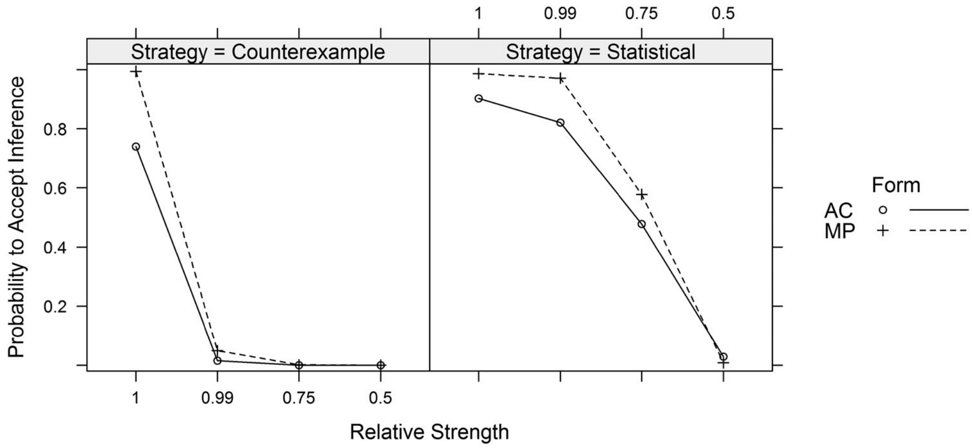

Figure 2. Number of accepted inferences in Study 1 (out of a total of 3) as a function of logical form and statistical information for counterexample and for statistical reasoners.

Taken together, we expect that logical form has less of an impact when statistical information is directly translated into probabilistic inference. In this second study, we extended Study 1 and examined explicitly probabilistic inferences using the same problems. Given the more direct relationship between information and inference in the present study, we expect that the relationship between logical form and inferential strategy is less strong. We replicated Study 1 with one difference. For the *Relative Strength* problems, we asked participants to indicate the probability of the conclusion being true on a scale from 0% to 100%.

Method

Participants

A total of 143 University students (49 males, 94 females: average age = 21 years, 5 months) took part in this experiment. Students were native French speakers at the Université du Québec à Montréal and all were volunteers.

Material

Four paper and pencil booklets were prepared. These were identical to the booklets used in study 1, with one exception. The response format for the relative strength problems followed the following pattern:

> The geologists have affirmed that: If a Trolyte is heated, then it will give off Philoben gas.
>
> Observation: A Trolyte is not heated.
>
> What is the probability that the Trolyte will not give off Philoben gas.

Immediately below this, participants were presented with a scale going from 0% to 100% increments of 10%. The strategy assessment problems used the same dichotomous format used in Study 1.

Procedure

Booklets were randomly distributed to entire classes. Students who wished to participate were told to take as much time as they needed to answer the questions.

Results and discussion

We first analyzed overall performance on the relative strength problems. We performed an ANOVA with mean probability as dependent variable with Relative Strength as a repeated measure and Form (MP, AC) and Order (Assessment first, Relative strength first) as between subjects variables.[1] This gave significant main effects of Order, F (1, 139) = 6.59, $p = .02$, $\eta_G^2 = .03$, and Relative Strength, F (2.02, 280.91) = 271.48, $p < .0001$, $\eta_G^2 = .47$. There was a marginally significant interaction between Relative Strength × Form, F (2.02, 280.91) = 2.93, $p = .05$, $\eta_G^2 = .009$, and a significant interaction between Relative Strength × Form × Order, F (2.02, 280.91) = 8.79, $p = .0002$, $\eta_G^2 = .03$. These effects

[1]Degrees of freedom are Greenhousse-Geisser corrected for repeated-measures factor with more than two levels. As effect size we report *generalized eta-squared*, η_G^2 (Bakeman 2005).

were modulated by strategy, and will be discussed in a subsequent analysis.

We then analysed performance on the *Strategy Assessment* problem set. Participants who rejected all of the 90% inferences and all of the 50% inferences were put into the *Counterexample* category. Participants for whom acceptance rates were greater on the 90% items than that on the 50% items were put into the *Statistical* category. A total of 49 participants were not grouped into one of these two categories, and these were eliminated from subsequent analyses which is based on the remaining 109 participants. We then calculated mean probabilities for the MP and the AC inferences as a function of relative strength for statistical and counterexample reasoning strategies.

We performed an ANOVA with mean probability as dependent variable with Relative Strength as a repeated measure and Form (MP, AC), Strategy (Counterexample, Statistical), and Order (Assessment first, Relative strength first) as between subjects variables. This gave significant main effects of Strategy, F (1, 101) = 4.12, $p = .04$, $\eta^2_G = .02$, and of Relative Strength, F (2.03, 204.93) = 241.46, $p < .0001$, $\eta^2_G = .53$, as well as significant interactions involving Form × Relative Strength, F (2.03, 204.93) = 3.43, $p = .02$, $\eta^2_G = .02$, and Strategy × Relative Strength, F (2.03, 204.93) = 4.79, $p = .009$, $\eta^2_G = .02$. However, we also observed several significant interactions involving Order: Order × Form, F (1, 101) = 4.36, $p = .04$, $\eta^2_G = .02$, Order × Strategy × Form, F (1, 101) = 11.69, $p = .0009$, $\eta^2_G = .06$, Order × Form × Relative Strength, F(2.03, 204.93) = 7.65, $p = .0006$, $\eta^2_G = .04$, and the four-way interaction of Order × Strategy × Form × Relative Strength, F (2.03, 203.93) = 3.61, $p = .03$, $\eta^2_G = .02$. Figure 3 shows the pattern resulting from the four-way interaction.

Overall, counterexample reasoners viewed all the inferences as more likely (M = 77.1%, SD = 9.43) than did statistical reasoners (M = 72.2%, SD = 13.50). As would be expected, average ratings directly mirrored relative strength (100% problems = 91.3%, SD = 20.12; 99% problems = 86.5%, SD = 20.89; 75% problems = 69.9%, SD = 11.66; 50% problems = 51.1%, SD = 9.93).

Inspection of Figure 3 reveals some further interesting findings. When considering the counterexample reasoners (upper row in Figure 3), Order had no significant effect (all post-hoc $p > .05$, employing the Bonferroni–Holm correction). Furthermore, we

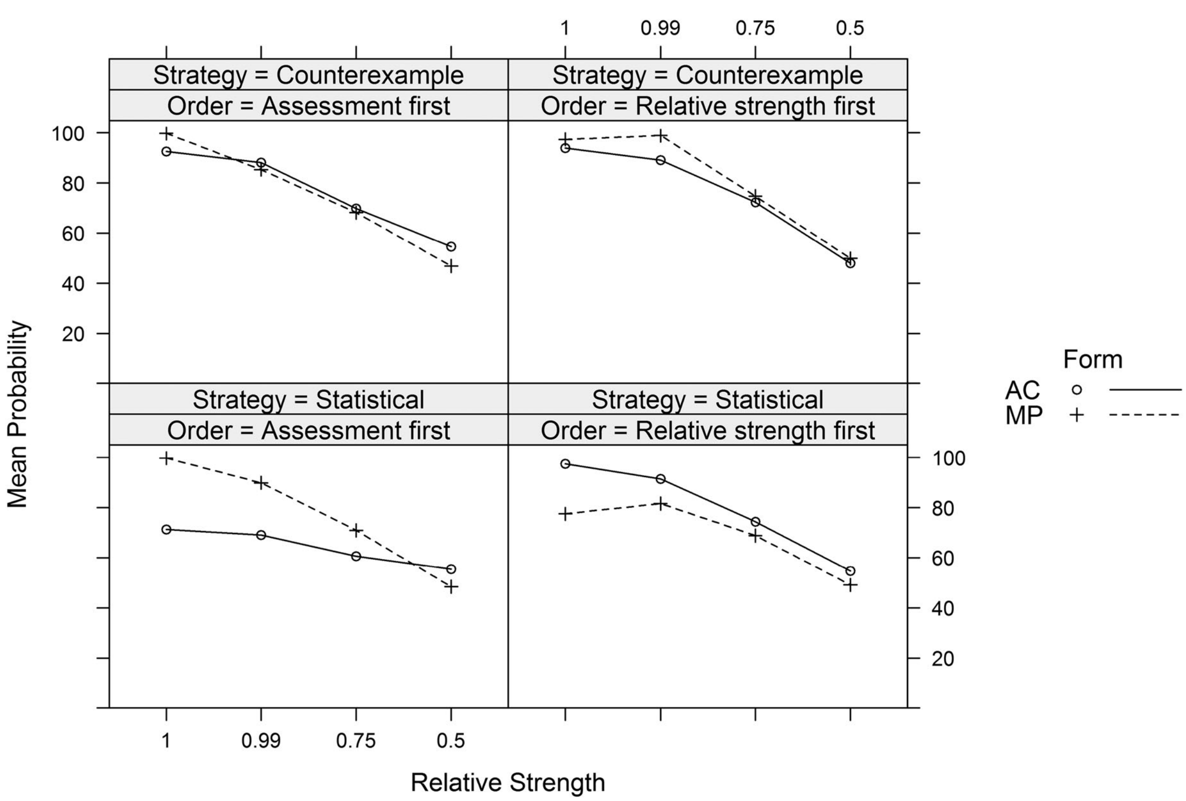

Figure 3. Mean estimated probability of conclusion in Study 2 as a function of logical form, statistical information, reasoning strategy, and presentation order.

found no effect of Logical Form (post-hoc $p > .05$), and a basically linear decrease across Relative Strength conditions (all $p < .05$). For the statistical reasoners (lower row), Order had a considerable effect. When the strategy assessment problems were presented first (left plot), probabilistic reasoners rate MP inferences as more probable than AC inferences (although, similarly to Study 1, this difference was concentrated on the 100% and 99% problems, $p < .003$). In the opposite order, there was a small effect of logical form for MP for the 100% problems ($p = .04$) but it pointed in the opposite direction, probabilistic reasoners rate AC as more probable than MP.

Overall, as predicted, the effect of logical form was definitely less extreme when people are asked to make explicitly probabilistic inferences that rely on direct statistical information than when they are asked to make dichotomous judgments of logical validity. These results nonetheless show that when making explicitly probabilistic inferences based on overt statistical information, logical form does have an effect, one that interacts with strategy use and order of problem presentation.

Finally, while we did not predict the order effect, it is consistent with our general hypothesis. The assessment problems used here required participants to transform explicit statistical information into dichotomous judgments of logical validity. We have assumed that such a process makes logical form a more relevant dimension than would be involved into a direct transformation of such information into a probabilistic evaluation. Thus, one interpretation of these results is that logical form has a very weak impact when making explicitly probabilistic inferences based on overt statistical information. However, the assessment problems could be seen to activate stronger consideration of logical form, which then interacts with reasoning strategy.

General discussion

Both the dual strategy and the dual source model focus on different forms of variability in the way that people make inferences. The former concentrates on the way that explicit and implicit statistical information is processed, while the latter suggests that implicit understanding of logical form has an influence. The present results show that understanding the way that people make inferences about deductive validity requires consideration of both of these factors. The results of Study 1 show that logical form influences deductions of validity relatively equally for both counterexample and statistical reasoners. In addition, these factors are both influenced similarly by the overall statistical patterns, with the strongest effects for both factors seen when conclusion likelihood is quite high. This could be due to a floor effect, so that when likelihood is low, judgments of validity become so low that these other forms of variation become less visible.

Although this is somewhat speculative, one way of understanding this interaction is to consider that the direct processing of statistical information is an active process that results in either an evaluation of the certainty of a conclusion or an estimation of the probability of a conclusion (depending on which strategy is employed). Effect of logical form can then be seen as a modulating factor that adjusts this evaluation by a percentage that translates the intuition that, all things being equal, under deductive instructions, an MP inference is stronger than an AC inference. Explaining this interaction in this way also explains the diminishing effect of logical form.

By contrast, the results of Study 2 show that logical form has a clear, but relatively small influence on probabilistic inferences based on explicit statistical information, and that this is concentrated among reasoners using a statistical strategy. This finding replicates results from work on the dual-source model (Singmann et al., 2016) in which it was found that for probabilistic inferences the vast majority of the variance is explained by the knowledge-based component. However, there are interactions between these different factors. One of the more interesting these is the order effect found with statistical reasoners. When the assessment problems are given initially, probabilistic assessments made by statistical reasoners show the same pattern as was found in Study 1, with very small differences in probabilistic assessments when these were given initially. Since the assessment problems require explicit deductive inferences, this is consistent with previous results showing interactions between deductive and probabilistic tasks (Markovits et al., 2015), although the specific form of this interaction requires some additional explanation.

Thus, although the question of just how to integrate these various factors into a single model of inferential behaviour remains open, taken together, these results show that a complete understanding of inferential behaviour requires minimally understanding the effect of reasoning strategy, logical form, and the explicit form of inference required of reasoners.

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