

Domain Effects on Interpretations of General Conditionals:

The Case of Mathematics

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Keywords:

conditional reasoning; general conditionals; interpretation; theory of mental models; new
paradigm

Abstract

Mathematics is often thought to have a unique association with certainty. The present study investigated a possible consequence of this association, namely that general conditionals are interpreted more deterministically in math than in other domains. To test this hypothesis, in two studies ($Ns = 146$ and 117), adults were presented general conditionals involving fictional categories in math and science and were asked to judge whether the conditionals were compatible with various frequencies of exceptions to them. Participants indicated that even rare exceptions (e.g., 1 exception per 99 confirming cases) would falsify a conditional (Studies 1 and 2), that a conditional could not be true and rare exceptions to it at the same time exist (Study 1), and that the truth of a conditional precluded the existence of even rare exceptions (Study 2), more when the conditionals involved math than science. The findings are consistent with the hypothesis that mathematical context is particularly likely to elicit deterministic interpretations of general conditionals. Implications of the findings for theories of conditional reasoning, and for individual differences in conditional reasoning, are discussed.

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Domain Effects on Interpretations of General Conditionals: The Case of Mathematics

In *Opus Majus*, Roger Bacon claimed that “In mathematics alone is there certainty without doubt” (Burke, 1928, p. 128). Similarly, Oaksford & Chater (2007), despite arguing that uncertainty is central to everyday reasoning, also observed that “mathematics appears to be about establishing certainties” (p. 51). These statements suggest that math has a strong and perhaps unique association with certainty. If so, how might this association affect reasoning?

The present study investigated a specific aspect of the above question, namely: Does the association of math with certainty affect how people interpret general conditionals? Conditionals are statements that express if-then relations. General conditionals are conditionals that refer to sets or types of things, as distinct from singular or specific conditionals, which refer to single cases. As their name suggests, general conditionals are useful for expressing generalities, which is critical in math (e.g., Hoyles & Küchemann, 2002; Stylianides et al., 2004) and many other domains, such as science. For example:

If water is frozen, then the water expands. (1)

(For $n > 1$) If $2^n - 2$ is divisible by n , then n is prime. (2)

(1) is general because it refers to water in general rather than a specific instance of water; similarly (2) refers to the set of numbers greater than 1 rather than a specific number.

How people interpret statements like (1) and (2) has been the subject of lively debate in psychology and other fields. One way of getting at this issue is to ask people what they would consider to falsify such statements. On a *deterministic* interpretation (Cariani & Rips, 2017; Goodwin, 2014; Johnson-Laird & Byrne, 2002; Khemlani & Johnson-Laird, 2022), such statements are falsified by the existence of any exceptions. This interpretation would render (1) and (2) false—water does not expand when frozen under very high pressure, and $2^{341} - 2$ is

divisible by 341 but 341 is not prime ($341 = 11 \times 31$)¹. In contrast, on a *probabilistic* interpretation (Douven et al., 2020; Evans & Over, 2004; Oaksford & Chater, 2020; Skovgaard-Olsen et al., 2016; Wang et al., 2022), a general conditional is not necessarily falsified by exceptions, provided that they are unlikely or rare. (1) and (2) could be considered true if interpreted in this way, because the exceptions to them are rare.

Human verbal reasoning depends on content and context as well as syntactic form (Dieussaert et al., 2002; Klauer et al., 2010; Pollard, 1982; Stenning & van Lambalgen, 2004). Thus, despite having the same syntactic form, conditionals may be interpreted differently in different domains. If math is uniquely associated with certainty, then deterministic interpretations may be more common, and probabilistic ones less common, in math than in other domains. If so, then rare exceptions should be thought to falsify general conditionals more often when they involve mathematical content than otherwise. The present study tested this prediction.

Below, I briefly describe prominent theoretical perspectives in the psychology of reasoning and discuss what these theories imply about interpretations of general conditionals. Then, I review empirical studies pertaining to deterministic and probabilistic interpretations of general conditionals. Last, I describe the present study in more detail.

Theoretical Perspectives on Interpretations of Conditionals

One prominent theory, the theory of mental models, originally proposed that a conditional “If p , then q ” means that p and q are both true, p and q are both false, or p is false and q is true (Johnson-Laird, 1983; Johnson-Laird & Byrne, 2002). The theory has recently been revised; in its newer formulation, the above conditional means that the three aforementioned cases are possible, whereas the remaining case—that p is true and q is false—is impossible

¹ 341 is the smallest composite number for which $2^n - 2$ is divisible by n .

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(Johnson-Laird et al., 2015; Khemlani et al., 2018). In reference to general conditionals, cases in which p is true and q is false would constitute exceptions. The stipulation that such cases are impossible implies that exceptions do not exist, since if they existed, they would be possible. Thus, in the theory of mental models, the interpretation of general conditionals is deterministic in the sense described above.

The theory allows that content and context may modulate the meaning of conditionals. For example, for any true conditional whose converse is also true (e.g., “If $n > 0$, then $n+1 > 1$ ”), it is impossible that p is false and q is true. Such a conditional would not be thought to imply that this impossible case is possible, nor would the impossibility of that case be thought to falsify the conditional. However, even in such cases, a conditional implies that exceptions are impossible, and the existence of exceptions would falsify a conditional.

Another group of theories, jointly referred to as “the new paradigm,” focuses more on degrees of belief than binary truth or falsehood. These theories see “belief as inherently uncertain and reasoning as concerned with updating our uncertain beliefs” and assume that “degrees of belief can be captured by probabilities” (Oaksford & Chater, 2020, p. 308). Specifically, one’s degree of belief in a conditional “If p , then q ” can be captured by the probability $P(\text{If } p, \text{ then } q)$. Many theorists (e.g., Evans & Over, 2004; Over, 2020) further assume an identity known as “the Equation” (Edgington, 1995), according to which the probability of a conditional equals the probability of its consequent conditional on its antecedent—that is, $P(\text{If } p, \text{ then } q) = P(q|p)$.

What do these assumptions imply about how people interpret general conditionals, specifically whether such conditionals should be thought to tolerate exceptions? The answer depends in part on how people convert degrees of belief into judgments of truth and falsehood. A reasonable approach is to “set a threshold such that degrees of belief larger than the threshold are

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regarded as sufficiently high to warrant a ‘true’ judgment, and degrees lower than the threshold result in a ‘false’ judgment” (Oberauer & Wilhelm, 2003, p. 685). Applying this approach to general conditionals, one would judge such conditionals to be true not only if no exceptions exist, but also if exceptions exist but are sufficiently rare that $P(q|p)$, and therefore degree of belief, exceed the threshold (Wang et al., 2022; Wang & Yao, 2018). Doing so would reflect a probabilistic interpretation in the sense described above.

In the above discussion, I have glossed over the distinction between asserting the truth of a general conditional for semantic or pragmatic reasons. In general, there is ongoing debate about whether particular phenomena in conditional reasoning should be attributed to semantics or pragmatics (e.g., Cruz & Over, 2023; Skovgaard-Olsen, 2020). This study is concerned with the conditions under which individuals claim that a general conditional is compatible with rare exceptions to it, whether they do so for semantic or pragmatic reasons. However, such claims are distinct from assertions of the truth of a conditional based on subjective belief in it when it is uncertain whether exceptions to it exist, as in the case of a mathematician maintaining the truth of a conjecture that has been neither proven nor disproven². Such assertions of truth are not the concern of the present study.

In summary, a deterministic interpretation of general conditionals, which renders them incompatible with the existence of even rare exceptions, is suggested by the theory of mental models. In contrast, a probabilistic interpretation, in which a general conditional can be said to be true even when rare exceptions to it exist, is suggested by theories in the new paradigm. Several recent empirical studies have contrasted these two views of general conditionals.

² I thank David Over for pointing out this distinction.

Studies on Deterministic and Probabilistic Interpretations of General Conditionals

First, Goodwin (2014) found evidence that by default, adults view general conditionals as incompatible with exceptions. When presented data in which $P(q|p)$ was less than 100%, participants described the data using general conditionals qualified by probabilistic language (e.g., “If a country has the virus, then it **probably** [emphasis added] has an annual per person income of less than \$500”). Only when $P(q|p)$ was 100% did participants use unqualified language. When told that a general conditional was true and asked to guess $P(q|p)$, most participants guessed 100%. Finally, most participants indicated that for a general conditional to be true, there must be no exceptions to it, and that even rare exceptions (e.g., $P(\neg q|p) = 4\%$ in Experiment 8) falsified a conditional. Goodwin (2014) interpreted these findings as consistent with the deterministic interpretation of conditionals posited by the theory of mental models.

Similar results were obtained by Wang, Over, and Liang (2022). When presented with descriptions of sets indicating that the sets included exceptions to a general conditional, large majorities of participants judged that these sets falsified the conditional. Further, when instructed to assume that a general conditional was true and asked whether, given this assumption, it was possible that the conditional referred to a set that included exceptions, large majorities said no.

However, two other studies yielded contrasting results (Cruz & Oberauer, 2014; Wang & Yao, 2018). First, participants in Cruz and Oberauer (2014) judged the probabilities that general conditionals and universally quantified statements (e.g., “All the Birnei that are from A have a bark with black lines”) were true of samples drawn from populations, based on information about the frequencies of different cases in the populations. In all the populations, $P(\neg q|p)$ was greater than 4%—that is, they included exceptions. Participants judged the conditionals much more likely to be true than the universally quantified statements. This result suggests that general

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conditionals were considered to tolerate exceptions more than universally quantified statements do, consistent with a probabilistic interpretation of the general conditionals.

Second, a study of Wang and Yao (2018) addressed a limitation shared by all of the above studies—namely, those studies did not include situations in which exceptions are specified to exist but to be extremely rare. In the first of two experiments, when told to assume that a general conditional (e.g., “If a card is round, then it is red”) was true, most participants judged that exceptions (e.g., “round blue cards”) were impossible. However, most of these participants also asserted that it was possible that such conditionals could refer to sets containing extremely rare exceptions (e.g., a set in which 1 out of 100 or 10 out of 1000 round cards were blue, implying $P(\neg q|p) = 1\%$, lower than the 4% rate of exceptions tested in and Cruz & Oberauer, 2014 and Goodwin, 2014). In the second experiment, most participants judged general conditionals to be falsified by the existence of exceptions, but most of them also judged the conditionals to be true when they referred to sets containing extremely rare exceptions.

To explain these apparently conflicting findings, Wang and Yao (2018) proposed that individuals interpret conditionals differently depending on context. Specifically, they argued that information about existence of exceptions, but not about their frequencies, created an abstract context, and that abstract context elicits deterministic interpretations of conditionals. Further, they argued that information about frequencies of exceptions constituted a concrete context, and that concrete context elicits probabilistic interpretations.

The Present Study

General conditionals in math typically are abstract in the sense referenced by Wang and Yao (2018). That is, such conditionals may be juxtaposed with information about the existence or nonexistence of cases (such as exceptions) that are relevant to the truth of the conditional, but

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are rarely juxtaposed with information about the frequencies of such cases. Thus, Wang and Yao's (2018) findings provide one reason to hypothesize that general conditionals may be interpreted more deterministically in math than in other domains.

Another rationale for the same hypothesis, which does not depend on whether frequency information is provided, is pragmatic. Mathematical conditionals are often encountered in educational settings, such as textbooks and classroom instruction. It is plausible that conditionals in such settings are typically intended deterministically and that students are aware of this intention. For example, if one reads in a textbook that “If m and n are even, then $m+n$ is even,” it seems unlikely that the textbook's author intended “If m and n are even, then $m+n$ is probably even.” Lacking evidence to the contrary, students might generalize from educational settings to assume that mathematical conditionals in other settings are also intended deterministically, and interpret them accordingly.

A third rationale for the above hypothesis involves the types of evidence that can be brought to bear in support of general conditionals in math. Consider how one might convince a nonbeliever that “If m and n are even, then $m+n$ is even.” One might appeal to types of justification that are available in other domains, such as authority (e.g., “teacher said so”), an example (e.g., “2 and 4 are even, and $2+4$ equals 6, which is even”), or induction from multiple examples. However, general conditionals in math—unlike most other domains—can also be proven deductively. Deductive proof is challenging, and most individuals are likely unable to generate valid deductive proofs of many, or even any, mathematical conditionals. Nevertheless, the awareness that mathematical conditionals can be proven deductively in principle could lead individuals to interpret conditionals deterministically more in math than in other domains³.

³ This argument presumes that individuals believe that deductive proof precludes the existence of exceptions. However, some individuals may not believe this, a point I return to in the General Discussion.

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Along similar lines, Skovgaard-Olsen (2020) recently speculated that in mathematical contexts, the conditional is interpreted as material implication (which is deterministic) due to the value placed on consistency and provability in such contexts.

To test the above hypothesis, in the present study, participants were presented general conditionals together with information about the relative frequencies of confirming cases, in which p and q were both true, and exceptions, in which p was true and q was false. Participants' task was to indicate whether the conditional was true given that the frequency information was true (Studies 1 and 2), whether the conditionals and the frequency information could both be true at once (Study 1), or whether the frequency information was possible given that the conditionals were true (Study 2). The above hypothesis implied that when the frequency of exceptions was low but not zero, negative responses—which indicate that a conditional is incompatible with exceptions—should be more common for mathematical than non-mathematical content.

The conditionals presented to participants involved fictional categories in math and science. Specifically, the math conditionals were about a fictional type of numbers called “spatial numbers,” which included sun, moon, and star numbers, and the science conditionals were about a fictional type of fruit called “wumpa fruit,” which included spiky, rough, and squishy wumpa fruit. These fictional categories were intended to convey the contextual distinction between math and science while preventing participants from basing their judgments on prior knowledge regarding the conditionals' content.

Some recent theoretical debates have hinged on whether a positive relation between p and q is required for “If p , then q ” to be judged as true (Cruz & Over, 2023; Douven et al., 2018; Skovgaard-Olsen et al., 2016). Identifying a logical or causal relation would require knowledge about the categories involved, and identifying a statistical relation would require information

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about the frequencies of cases in which p is false. These types of information were not provided in the present study, so participants could not determine whether p and q were related and, if so, whether the relation was positive. Thus, the study could not be directly informative regarding the theoretical debates mentioned above. However, participants' responses may have reflected, in part, baseline assumptions about the likelihood of p and q being related based on background knowledge about conditionals in each domain (math and science).

Study 1

Participants in Study 1 completed a Set-Based Truth Task (Goodwin, 2014; Wang et al., 2022; Wang & Yao, 2018), a Collective Possibility Task (Goodwin & Johnson-Laird, 2018), and an Algebra Word Problem Task. The first two tasks were designed to test the central hypothesis described in the Introduction. The third task was intended to test a secondary hypothesis about individual differences, described below.

In the Set-Based Truth Task, participants were provided a general conditional followed by information about the frequencies of confirming cases and exceptions. The task was to judge whether the frequency information rendered the conditional true or false. It was predicted that when exceptions were rare ($P(\neg q|p) = 1\%$ or 10%), they would be judged to falsify conditionals more often when the conditionals involved math than science (H1.1).

In the Collective Possibility Task, participants were again provided with a general conditional and a statement about the relative frequencies of confirming cases and exceptions. Their task was to decide whether the conditional and the frequency information could both be true at once. It was predicted that exceptions, when rare, would be judged incompatible with conditionals more often when the conditionals involved math than science (H1.2).

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A secondary goal of Study 1 was to investigate individual differences in participants' interpretations of general conditionals. If math is associated with deterministic interpretations more than other domains are, then such interpretations may also be more common among individuals who are high-achieving in math than among other individuals. To test this prediction, participants completed an Algebra Word Problem Task, and accuracies on that task were used to classify participants as high or low math achievers. It was predicted that high math achievers would be more likely than low math achievers to judge that rare exceptions falsify conditionals in the Set-Based Truth Task (H1.3) and that rare exceptions are incompatible with conditionals in the Collective Possibility Task (H1.4).

This study was [preregistered](#) at Open Science Foundation. The preregistration was followed unless stated otherwise, and reported analyses were preregistered unless described as exploratory. [Stimuli, data, and analysis code](#) are available at Open Science Foundation.

Method

Participants

Participants were 146 students (43 male, 103 female) at XXX University who participated for psychology course credit. A target sample of 135 was determined based on power analysis conducted using G*Power 3.1 (Faul et al., 2007), which indicated that after up to 5% exclusions, this sample would yield at least 80% power to detect the effects predicted in all preregistered analyses (see preregistration for details). Eleven additional participants had signed up when recruitment was stopped, so these extra participants were included in the sample.

Regardless of how one interprets a general conditional, it should be perceived as incompatible with higher frequencies of exceptions at least as much as with lower frequencies of exceptions. Thus, as preregistered, participants were excluded from analyses of a given task if,

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for either math or science trials, they answered “false” (on the Set-Based Truth Task) or “no” (on the Collective Possibility Task) more often on trials involving 0%, 1%, or 10% exceptions than on trials involving 50% or 90% exceptions. The numbers of participants excluded for this reason were 4 and 7 for the Set-Based Truth Task and Collective Possibility Task, respectively.

Tasks and Materials

Set-Based Truth Task. In the math version of the task, participants were told that a mathematician was using a computer program to test hypotheses about three types of numbers: sun numbers, moon numbers, and star numbers. In the science version, participants were told that a scientist was using DNA analysis to test hypotheses about three types of wumpa fruit: spiky, rough, and squishy. On each trial, participants would see a hypothesis followed by output of the computer program or DNA analysis. Participants were to judge whether the hypothesis was true or false, assuming that the program or analysis output was true with absolute certainty.

The hypotheses were general conditionals such as “If a number is a sun number, then the number is prime” and “If a wumpa is spiky, then it has green seeds.” The program or analysis output indicated the relative frequencies of confirming cases and exceptions in percentage form, such as “99% of sun numbers are prime; 1% of sun numbers are not prime” or “99% of spiky wumpas have green seeds; 1% of spiky wumpas do not have green seeds.” There were six conditionals—three for math and three for science—and five frequencies of exceptions: 0%, 1%, 10%, 50%, or 90%. Participants completed one trial for each combination of conditional with exception frequency, for a total of 15 trials per domain.

Collective Possibility Task. In the math version of the task, participants were told that a mathematician was considering various hypotheses about sun numbers, moon numbers, and star numbers. In the science version, participants were told that a scientist was considering various

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hypotheses about spiky, rough, and squishy wumpa fruit. On each trial, participants would see two hypotheses about one type of number or wumpa fruit. Participants' task was to decide whether it was possible for both hypotheses to be true at once. They were to answer "no" if the hypotheses contradicted each other and "yes" otherwise.

On each trial, the first hypothesis was a general conditional like the ones presented in the Set-Based Truth Task, and the second hypothesis was a statement about the relative frequencies of confirming cases and exceptions. For example, in one trial involving math content, the hypotheses were "If a number is a moon number, then the number is positive" and "99% of moon numbers are positive; 1% of moon numbers are not positive." In one trial involving science content, the hypotheses were "If a wumpa is rough, then it tastes sweet" and "99% of rough wumpas taste sweet; 1% of rough wumpas do not taste sweet." As in the Set-Based Truth Task, there were three conditionals per domain and five frequencies of exceptions (0%, 1%, 10%, 50%, 90%) per conditional, yielding 15 trials per domain.

Algebra Word Problem Task. This task consisted of 16 multiple choice items released from the math portion of the eighth grade and twelfth grade versions of the National Assessment of Educational Progress (NAEP). The task included 2, 9, and 5 items classified by NAEP as "easy," "medium," and "hard," respectively. Cronbach's alpha in this sample was .76. Mean accuracy was .70 ($SD = .20$; chance = .20).

Procedure

Participants completed the math version of the Set-Based Truth Task and Collective Possibility Task followed by the science version of the two tasks, or vice versa. Whether the math tasks or science tasks were presented first was counterbalanced across participants. For a given participant, the two tasks were presented in the same order for math and science, but the

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order of the two tasks was counterbalanced across participants. Within each version of each task, the five trials relating to a given conditional were presented in a block. The order of these blocks, and of trials within each block, was randomized for each participant.

The Algebra Word Problem Task was presented after the above tasks. Participants were given paper and pencil, but were not allowed to use a calculator. Items appeared in a fixed order.

All tasks were presented on a desktop computer via Qualtrics. Instructions were delivered orally by an experimenter. The experimenter was present during the Set-Based Truth Task and Collective Possibility Task, but left the room during the Algebra Word Problem Task.

Results

Set-Based Truth Task

“False” responses on this task indicate a belief that a conditional is falsified by a certain frequency of exceptions to it. Percent false responses on trials involving low but nonzero rates of exceptions—that is, 1% or 10%—were submitted to *ANOVA* with domain (math or science) and percent exceptions (1% or 10%) as within-participants factors. Consistent with H1.1 and as shown in Figure 1A, “false” responses were more common for math than science conditionals (81% vs. 70%), $F(1, 141) = 18.5, p < .001, \eta_g^2 = .017$. “False” responses were also more common when there were 10% than 1% exceptions (80% vs. 72%), $F(1, 141) = 18.9, p < .001, \eta_g^2 = .009$. Finally, the effect of domain was greater for 1% exceptions (79% vs. 65%) than 10% exceptions (84% vs. 76%), $F(1, 141) = 6.8, p = .010, \eta_g^2 = .001$. Planned contrasts found that the domain effect was significant in both cases (1% exceptions: $p < .001$; 10% exceptions: $p = .005$).

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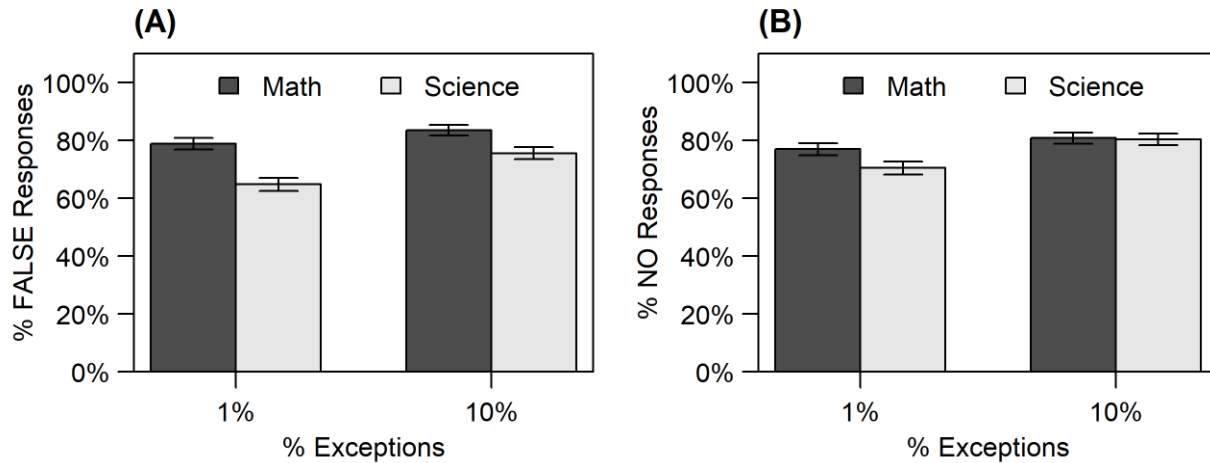


Figure 1. (A) Percent “false” responses on the Set-Based Truth Task and (B) Percent “no” responses on the Collective Possibility Task, by Domain and Percent Exceptions (Study 1).

To test for effects of math achievement on how participants interpreted the conditionals, participants were classified as high or low math achievers via a median split on accuracy on the Algebra Word Problem task. Then, math achievement group was added as a between-participants factor to the above *ANOVA*. Contrary to H1.3, no effects involving this factor were found, $ps > .49^4$.

An individual who interprets general conditionals deterministically should respond “true” on all trials involving 0% exceptions and “false” on all other trials. Exploratory analyses were conducted to assess the prevalence of this response pattern. Separately for math and science, the percentage of participants displaying the above pattern was calculated and compared to 50%

⁴ Experience in math education might affect interpretations of conditionals in the manner originally predicted for math achievement, because interpretations that are consistent with formal logic are often emphasized in higher-level math courses (I thank an anonymous reviewer for this suggestion). Exploratory analyses were conducted to test this possibility. Participants in this study and Study 2 were classified into two groups based on whether their undergraduate major typically involves substantial coursework in math or logic (e.g., mathematics, physics, chemistry, engineering, economics, finance, philosophy, etc.) or not. The *ANOVAs* reported here and in the next subsection were rerun with the aforementioned group classification replacing math achievement as a factor, and the *ANOVAs* reported in Study 2 were rerun with group classification added as a factor. No effects involving the group classification were found in any analysis.

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using a one-sample binomial test. For math, more than half of participants (75%, 95% $CI = [67\%, 82\%]$) displayed the above pattern, $p < .001$. For science, the pattern was less common, but still accounted for over half of participants (62%, 95% $CI = [53\%, 70\%]$), $p = .005$.

Collective Possibility Task

“No” responses on this task indicate a belief that a conditional and a certain frequency of exceptions to it are mutually contradictory. Percent “no” responses on trials involving 1% or 10% exceptions were submitted to *ANOVA* with domain and percent exceptions as within-participants factors. The data relevant to this analysis are shown in Figure 1B. The main effect of domain was not significant, $p = .17$. However, domain interacted with percent exceptions, $F(1, 138) = 8.5, p = .006, \eta_g^2 = .001$. Planned contrasts found that “no” responses were more common for math than science conditionals for 1% exceptions (77% vs. 70%, $p = .019$), consistent with H1.2, but not for 10% exceptions (81% vs. 80%). Finally, “no” responses were more common when there were 10% than 1% exceptions, $F(1, 138) = 15.1, p < .001, \eta_g^2 = .007$.

As for the Set-Based Truth Task, math achievement group was added as a factor to the *ANOVA* to test for effects of math achievement on interpretations of the conditionals. However, contrary to H1.4, no effects involving this factor were found, $ps > .08$.

Finally, as for the Set-Based Truth Task, exploratory analyses were conducted to assess the prevalence of deterministic response patterns. For the Collective Possibility Task, the deterministic pattern was responding “yes” on all trials involving 0% exceptions and “no” on all other trials. This pattern accounted for a majority of participants in both math (68%, 95% $CI = [59\%, 75\%]$, $p < .001$) and science (63%, 95% $CI = [55\%, 71\%]$, $p = .005$).

Discussion

The Set-Based Truth Task revealed more deterministic interpretations of general conditionals in math than in science, as predicted. Study 2 attempted to replicate this finding.

A similar effect of domain appeared in the Collective Possibility Task, but the effect appeared weaker and was statistically significant only when exceptions were specified to be extremely rare (1%) rather than only somewhat rare (10%). A possible explanation is that the Collective Possibility Task is a relatively imprecise measure of how individuals interpret general conditionals. The instruction to judge whether a conditional and a statement about frequency information could both be true at once left open whether participants should focus on the conditional first and the frequency information second, or vice versa. This ambiguity may have increased between-participant variability. Further, participants who focused on the frequency information first may not have processed the conditional deeply. To address these possible issues, a revised version of this task was developed for Study 2.

Both tasks revealed substantial individual differences in interpretations of general conditionals, with most participants displaying deterministic interpretations but a substantial minority displaying probabilistic interpretations. These results converge with several previous studies that found considerable variation in how people interpret general conditionals (Goodwin, 2014, Experiments 7 and 8; Wang et al., 2022; Wang & Yao, 2018). However, no evidence was found that the above differences were related to differences in math achievement. This null result contrasts with findings of Evans et al. (2007), who found that individuals higher in general cognitive ability were more likely to judge singular conditionals to be rendered true by confirming cases and false by exceptions. Individual differences in interpretations of conditionals may relate more to general cognitive ability than to math-specific ability.

Study 2

Participants in Study 2 completed the same Set-Based Truth Task as in Study 1, and a revised version of the Collective Possibility Task called the Possibility of Exceptions Task. In this task, participants were again presented a general conditional followed by information about the frequency of exceptions. However, rather than being asked whether both statements could be true at once, participants were told to assume that the conditional was true and to judge whether, given the truth of the conditional, the frequency information was possible. This change was intended to simplify the task by encouraging participants to attend to one statement at a time and to decrease irrelevant variability by encouraging all participants to consider the statements in the same order—first the conditional, then the frequency information.

It was predicted that in the Set-Based Truth Task, conditionals would be perceived as falsified by rare (1% or 10%) exceptions more for math than science, as in Study 1 (H2.1). Further, it was predicted that the Possibility of Exceptions Task would reveal an effect analogous to the one predicted for the Collective Possibility Task in Study 1. That is, given the truth of a conditional, rare exceptions to it would be considered impossible more often for math than science (H2.2).

Exploratory analyses of both tasks in Study 1 found that more than half of participants displayed purely deterministic responses—that is, responding “true” or “yes” on trials involving 0% exceptions and “false” or “no” on all other trials. Study 2 aimed to replicate this finding for math conditionals using preregistered analyses. Specifically, it was predicted that most participants would display deterministic responses for math conditionals in both the Set-Based Truth Task (H2.3) and the Possibility of Exceptions Task (H2.4). Although this pattern was also found for science conditionals in Study 1, an analogous prediction was not made for science

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conditionals, because finding deterministic responses to be dominant for science conditionals would neither support nor undermine the central hypothesis of this study.

Like Study 1, Study 2 was [preregistered](#), the preregistration was followed unless stated otherwise, reported analyses were preregistered unless described as exploratory, and [stimuli, data, and analysis code](#) are available at Open Science Foundation.

Method

Participants

Participants were 117 adults (51 men, 61 women, 5 other) recruited through Prolific, an online recruitment and survey platform. To increase comparability of the results to those of Study 1, the sample was restricted to individuals currently residing in the US or UK, aged 18 to 30, and enrolled in college or university. A target sample of 116 was determined based on *a priori* power analysis conducted using G*Power 3.1 (Faul et al., 2007), which indicated that this sample, after up to 10% exclusions, would yield at least 80% power to detect all predicted effects (see preregistration for details). One extra participant was recruited due to an administrative error and was included in the final sample.

As in Study 1, for each task, participants were excluded from analyses of the task if, on either math or science trials, they answered “false” or “no” more often on trials involving rare (0%, 1%, or 10%) than frequent (50% or 90%) exceptions. The numbers of participants excluded for this reason were 6 for the Set-Based Truth Task and 8 for the Possibility of Exceptions Task.

Tasks and Materials

Set-Based Truth Task. This task was identical to the Set-Based Truth Task in Study 1, except for minor changes to the wording of the instructions.

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Possibility of Exceptions Task. This task was identical to the Collective Possibility Task in Study 1 except as follows. First, the conditional presented on each trial was not described as a hypothesis; instead, participants were instructed to suppose that the conditional was true. Second, the statement describing frequency information was also not described as a hypothesis; instead, participants were asked whether it was possible for that statement to be true, given that the conditional was true. The instructions preceding the task were revised to reflect these changes.

Procedure

Participants completed the math version of the Set-Based Truth Task and Possibility of Exceptions Task followed by the science version of the two tasks, or vice versa. The order of tasks, and of trials within each task, was varied across participants in the same way as in Study 1. All tasks were presented online via Qualtrics. Participants accessed the study through their own electronic devices and completed the study without experimenter supervision.

Results

Set-Based Truth Task

As in Study 1, percent “false” responses on trials involving 1% or 10% exceptions were submitted to *ANOVA* with domain and percent exceptions as within-participants factors. Consistent with H2.1 and as shown in Figure 2A, “false” responses were more common for math than science conditionals (72% vs. 62%), $F(1, 110) = 9.8, p = .002, \eta_g^2 = .010$. This effect was larger for 1% than 10% exceptions (68% vs. 54% and 77% vs. 71% respectively), $F(1, 110) = 5.5, p = .021, \eta_g^2 = .002$. Contrasts performed on the ANOVA output found the effect of domain to be significant for 1% exceptions, $p < .001$, but not for 10% exceptions, $p = .14$. Finally, “false” responses were more common for 10% than 1% exceptions (74% vs. 61%), $F(1, 110) = 26.5, p < .001, \eta_g^2 = .021$.

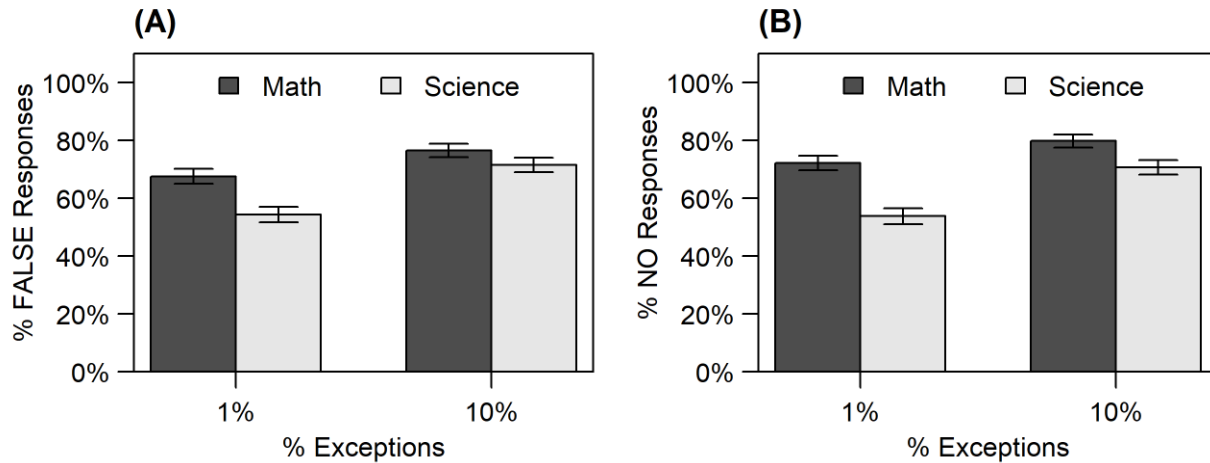


Figure 2. (A) Percent “false” responses on the Set-Based Truth Task and (B) Percent “no” responses on the Possibility of Exceptions Task, by Domain and Percent Exceptions (Study 2).

63% of participants (95% $CI = [53\%, 72\%]$) displayed purely deterministic responses for math conditionals, that is, they responded “true” when the frequency of exceptions was 0% and “false” otherwise. Consistent with H2.3, this proportion was greater than 50% by a one-sample binomial test, $p = .008$. As an exploratory analysis, the analogous proportion for science conditionals (49%, 95% $CI = [39\%, 58\%]$) was compared to 50% by a one-sample binomial test. The result was not significant, $p = .85$.

Possibility of Exceptions Task

“No” responses on this task indicate a belief that, given the truth of a conditional, a certain frequency of exceptions to it is impossible. Percent “no” responses on trials involving 1% or 10% exceptions were submitted to *ANOVA* with domain and percent exceptions as within-participants factors. Consistent with H2.2 and as shown in Figure 2B, “no” responses were more common for math than science conditionals (76% vs. 62%), $F(1, 108) = 15.7, p < .001, \eta_g^2 = .025$. This effect was larger for 1% than 10% exceptions (72% vs. 54% and 80% vs. 71% respectively), $F(1, 108) = 27.0, p < .001, \eta_g^2 = .020$. Planned contrasts found the effect of domain

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to be significant in both cases, $p < .001$ for 1% exceptions and $p = .018$ for 10% exceptions.

Finally, “no” responses were more common for 10% than 1% exceptions (75% vs. 63%), $F(1, 108) = 7.6, p = .007, \eta_g^2 = .003$.

63% of participants (95% $CI = [54\%, 72\%]$) displayed purely deterministic responses for math conditionals, that is, they responded “yes” when the frequency of exceptions was 0% and “false” otherwise. Consistent with H2.4, this proportion was greater than 50% by a one-sample binomial test, $p = .007$. An exploratory analysis found no evidence that the analogous proportion for science conditionals (45%, 95% $CI = [35\%, 55\%]$) differed from 50%, $p = .34$.

Discussion

Results from the Set-Based Truth Task replicated the Study 1 finding that rare exceptions were considered to falsify general conditionals more in math than science. The Possibility of Exceptions task yielded converging results indicating that the truth of a general conditional was thought to preclude even rare exceptions to it more in math than in science. Results from the Possibility of Exceptions Task in Study 2 seemed stronger than those from the Collective Possibility Task in Study 1, suggesting that the former task may be a more sensitive measure of how individuals interpret conditionals.

Both tasks in Study 2 found that over half of individuals interpreted math conditionals strictly deterministically, thus replicating in preregistered analyses the results of analogous exploratory analyses in Study 1. In contrast, while Study 1 similarly found that over half of individuals interpreted science conditionals strictly deterministically, this was not the case with either task in Study 2. This null result is consistent with the general point that general conditionals are more likely to be interpreted deterministically in math than in science.

General Discussion

Two studies investigated adults' interpretations of general conditionals involving math and science. In both studies, participants indicated that a conditional was falsified by rare exceptions to it more often when the conditional involved math than science. Similarly, participants claimed in Study 1 that it was impossible for a conditional to be true and at the same time for rare exceptions to it exist, and in Study 2 that if a conditional was true it was impossible for rare exceptions to it to exist, more often when the conditionals involved math than science. Below, I discuss implications of these findings for how people interpret conditionals in math, theories of conditional reasoning, and individual differences in conditional reasoning.

Implications for How People Interpret Conditionals in Math

The present findings suggest that general conditionals elicit more deterministic interpretations in math than in other domains. Of all domains to which math might have been compared, science is a relatively stringent benchmark for comparison. Both are domains in which certainty, and related attributes such as precision and rigor, are highly valued. Consequently, one might expect deterministic interpretations of conditionals to be more common in both of these domains than in everyday life, although this expectation could not be confirmed in the present study because everyday conditionals were not included in it. If so, the present findings suggesting that such interpretations are even more common for mathematical than scientific conditionals are a testament to the unique association of math with certainty.

The manipulation used to convey mathematical or scientific context was fairly minimal. The conditionals involved fictional categories about which participants could not have relevant prior knowledge. The tasks did not require attention to the content of the conditionals. The tasks were performed in settings (a psychology laboratory in Study 1, an online survey in Study 2) that

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are not usually associated with either math or science. Nevertheless, the different cover stories provided to participants (e.g., stories involving a mathematician or a scientist testing hypotheses), differences in the types of categories that appeared in the conditionals (e.g., “numbers” versus “fruit”), and differences in the features attributed to these categories (e.g., “prime” or “sour”) were apparently sufficient to convey different contexts and thereby elicit different interpretations of the conditionals.

The present study joins many others in suggesting that interpretations of conditionals vary with context (Cariani & Rips, 2017; Dieussaert et al., 2002; Fugard et al., 2011; Johnson-Laird & Byrne, 2002; Markovits et al., 2019; Stenning & van Lambalgen, 2004). Most pertinent, like the present study, Wang and Yao (2018) proposed that individuals adopt either deterministic or probabilistic interpretations of general conditionals depending on context. However, their findings and the present ones differ in the details. For example, their Experiment 2 found that most participants considered a conditional to be false if there were any exceptions to it, but also to be true if there was one exception per 99 confirming cases. Wang and Yao (2018) concluded that frequency information creates a concrete context that elicits probabilistic interpretations of conditionals. In the present study, though, most participants consistently displayed deterministic interpretations of math conditionals even though frequency information was presented. (Over half also did so for science conditionals in Study 1, but not in Study 2.) Evidently, factors other than frequency information can affect whether conditionals are interpreted deterministically or probabilistically; domain appears to be one such factor.

What could be the source of the domain effects found in the present study? As described in the Introduction, conditionals could be interpreted more deterministically in math than in other domains because (1) such conditionals are rarely accompanied by frequency information; (2)

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authoritative sources of mathematical information, such as textbooks and teachers, are understood by math learners to intend a deterministic interpretation; or (3) mathematical conditionals are known to be provable by deduction, and deductive proof is known to preclude the existence of any exceptions whatsoever. Explanation (1) could apply in some cases, but cannot account for the present findings because frequency information was presented together with all conditionals in the present study. Explanations (2) and (3) are both compatible with the present findings (though see the section regarding individual differences below for possible difficulties with explanation (3)).

Implications for Theories of Conditional Reasoning

The present findings show that general conditionals are interpreted differently as a function of the domain to which they belong. Further, such domain effects can occur even when individuals have no prior knowledge about the categories to which the conditionals refer, and even if relevant frequency information is equally available in different domains. These results do not necessarily support any theory of conditionals over others, but rather constitute phenomena that each theory must explain. Theories that assume general conditionals are interpreted deterministically by default must explain how such interpretations could be less common in some domains than in math; theories that assume general conditionals are interpreted probabilistically by default must explain how such interpretations could be less common in math than in other domains. Below, I consider how several theories of conditional reasoning might accommodate the present findings.

First, the theory of mental models assumes that the core meaning of a conditional implies the impossibility of exceptions (Johnson-Laird, 1983; Johnson-Laird et al., 2015; Johnson-Laird & Byrne, 2002; Khemlani et al., 2018). Context may modify this core meaning through

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modulation, which can yield interpretations that tolerate exceptions. Thus, modulation could cause conditionals to be interpreted less deterministically in some contexts than in the core meaning. Importantly, however, modulation depends on “general knowledge and knowledge of context—which is represented in explicit models of what is possible” (Johnson-Laird & Byrne, 2002, p. 673). It is therefore unclear whether modulation can modify the interpretations of conditionals regarding categories about which individuals have no prior knowledge about what is or is not possible, as was in the case in the present study. Perhaps, the ways in which interpretations of conditionals are typically modulated in a given domain when familiar content is involved may be extended to conditionals in the same domain even when unfamiliar content is involved. Future research might test this possibility.

Second, according to suppositional accounts (Evans et al., 2005; Evans & Over, 2004; Over & Cruz, 2023), one’s degree of belief in “If p , then q ” is equal to one’s estimate of $P(q|p)$. If asked whether a general conditional is true given a certain value for $P(q|p)$ (as in the Set-Based Truth Task) or whether a certain value for $P(q|p)$ is possible given that a conditional is true (as in the Possibility of Exceptions Task and (less directly) the Collective Possibility Task), one presumably answers “yes” if the value given for $P(q|p)$ exceeds some threshold and “no” otherwise (Wang et al., 2022). This threshold could vary with context (e.g., Wang & Yao, 2018). Thus, the present findings could be explained by assuming the threshold value to be higher in math than other domains. A challenge in this framework is to provide a mechanism by which the threshold value can be affected by a conditional’s domain.

Third, according to inferentialist accounts, “If p , then q ” is considered true when there a sufficiently strong inferential connection from p to q (Douven et al., 2018, 2020; Skovgaard-Olsen et al., 2016). This connection can be statistical (i.e., an inductive connection), so the

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domain effects found in the present study could reflect domain-related differences in threshold values as described above. However, the inferential connection alternatively can reflect p being the best explanation for q (i.e., an abductive connection) or p logically implying q (i.e., a deductive connection). These possibilities suggest another explanation of the present findings, namely that domain constrains the types of inferential connection that conditionals are considered to represent, such that conditionals in general may express inductive, abductive, or deductive connections, but conditionals in math express deductive connections exclusively. Because deductive connections preclude exceptions, whereas inductive and abductive connections do not, the above assumption could explain the domain effects found in the present study.

Finally, dual-strategy approaches (Markovits et al., 2012, 2017; Verschueren et al., 2005) maintain that individuals evaluate conditional inferences in two ways, one heuristic and relying on probabilistic information, the other analytic and relying on generation of concrete counterexamples. This distinction between inference strategies is analogous to the present study's distinction between probabilistic and deterministic interpretations of conditionals. To explain the present findings, we might assume that the likelihood of adopting a given interpretation (probabilistic or deterministic) in a given domain depends on how frequently the analogous inference strategy (heuristic or analytic) is used in that domain. More specifically, if an analytic inference strategy is used in math more often than in other domains, individuals might consequently adopt a deterministic interpretation of conditionals more in math than in other domains.

Implications for Individual Differences in Conditional Reasoning

Interpretations of conditionals seem to vary substantially not only among domains, but also among individuals (Evans et al., 2007; Oberauer et al., 2007; Skovgaard-Olsen et al., 2019). For example, in Goodwin's (2014) Experiment 8, when asked to evaluate general conditionals with respect to sets in which $P(\neg q|p)$ was 10%, most participants judged the conditionals to be false, but 9% and 31% of participants said the conditionals were true or neither true nor false, respectively. When asked a similar question in Wang and Yao's (2018) Experiment 2, again most participants judged the conditionals to be false, but 10% to 18% of participants said the conditionals were true (the "neither" option was not offered in this experiment). Thus, even in situations that typically elicit deterministic interpretations of general conditionals, substantial minorities of individuals still seem to adopt probabilistic interpretations thereof.

The same was true in the present study, in fact to a greater degree than in the studies just described. When evaluating conditionals when $P(\neg q|p)$ was said to be 10%, the conditionals were perceived as true by 20% and 26% of participants in Studies 1 and 2, respectively. These percentages were only slightly lower—16% and 23%—for conditionals involving math content. Consistent with these data reflecting probabilistic interpretations by some participants, both math and science conditionals were considered falsified more when $P(\neg q|p)$ was 10% than when it was 1%⁵, although these two situations are equally falsifying according to a deterministic interpretation of conditionals.

This result dovetails with findings from the math education literature, indicating that some learners do not consider deductive proof to establish with certainty that a claim is true in all

⁵ In Study 1, the percentages of "false" responses on the Set-Based Truth Task for 10% and 1% exceptions were 84% and 79% for math conditionals and 76% and 65% for science conditionals. In Study 2, the corresponding percentages were 77% and 68% for math conditionals and 71% and 54% for science conditionals.

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cases. For example, in qualitative interviews with high school students in reference to empirical arguments for and deductive proofs of statements about geometry, Chazan (1993) identified several students who believed that “deductive proof provides no safety from counterexamples,” a belief exemplified by one student who claimed “there is no way to prove a statement for everything” (p. 372). Similarly, some secondary math teachers consider that contravening evidence may exist even for statements that have been proven deductively (Knuth, 2002), and even doctoral students in math do not always derive certainty from deductive proof (Weber et al., 2022). If some individuals believe that exceptions may exist even for deductively proven statements, it is not surprising that some think so for statements that have not been proven but merely asserted by an experimenter. An interesting question for future research is whether a belief that exceptions are always possible constitutes a stable dimension of individual differences and, if so, what other factors drive such differences.

Conclusion

Perfect certainty is rare in everyday life, but not in math. This distinctive characteristic of math has consequences for how people reason, specifically for how they interpret conditionals. Although math may be unique in its association with certainty, it is likely not unique in eliciting interpretations of logical statements that differ from the interpretations prevalent in other domains. Domain effects on interpretations of statements can be driven not only by individuals’ knowledge about the statements’ specific content, but also by expectations associated with the entire domain. Future research should explore such effects for other domains as well.

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