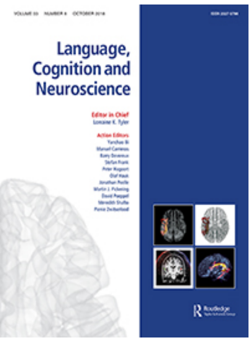

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Using the visual-world paradigm to explore the meaning of conditionals in natural language

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ABSTRACT

This paper reports three eye-tracking experiments using the visual world paradigm to explore the meaning of conditionals in Mandarin Chinese. Experiment 1 found that, when all the tokens were actually true in the experimental setting, the conditional connective *if … then …* didn't elicit significantly more anticipatory fixations than the conjunctive connective *… and …* on a token that is appropriately to be merged by the sentential connectives. By contrast, Experiments 2 and 3 found that, when a token was designed as hypothetically but not actually true in the experimental setting, the conditional connective elicited significantly more anticipatory fixations than the conjunctive connective on this hypothetical token. The implications of the experimental paradigm and the observed results were then discussed in relation to theories of conditionals, and to models of rationality in general.

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Conditionals; conjunctions; visual world paradigm; hypothetical thinking; Mandarin Chinese

One important goal in the study of human language is to explain how simple propositions are recursively merged into complex statements (Elqayam & Evans, 2011; Evans, 2002). In a given situation, a simple proposition is either true or false. If there are two propositions A and C (1a–b), then four distinct possibilities are involved in a given situation: AC, ¬AC, ¬A¬C, A¬C such as (2a–d), where ¬ means false. Sentential connectives like *if* and *and* in English are linguistic markers that merge two propositions into complex statements, such as a conjunction *A and C* as in (3a) and a conditional *if A, then C* as in (3b). In classical logic and other human rationality frameworks, the logical conjunction is defined as A&C and the material conditional is defined as A⊃C. The logical conjunction A&C is true if and only if the two merged conjuncts A and B are both true, while the conditional A⊃C is false only when A is true and C is false i.e. A¬C, and is true otherwise. In human language, the truth conditions of the conjunction *A and C* (3a) are parallel to the meaning of the logical conjunction A&C as defined in classical logic. However, theories differ in how the conditional (3b) is comprehended (such as, Evans, 2002; Johnson-Laird, Khemlani, & Goodwin, 2015).

(1) Two propositions
    (a) A: *The animal is a goldfish.*
    (b) C: *The animal has a banana.*

(2) Four possibilities
    (a) AC: The animal is a goldfish. The animal has a banana.
    (b) ¬A¬C$_2$: The animal is a swan. The animal has a feather.
    (c) ¬AC: The animal is a swan. The animal has a banana.
    (d) A¬C: The animal is a goldfish. The animal has a feather.

(3) The two complex statements
    (a) Conjunction: *The animal is a goldfish, and it has a banana.*
    (b) Conditional: *If the animal is a goldfish, then it has a banana.*

According to the mental model theory (e.g. Johnson-Laird, 1980, 2005, 2010; Johnson-Laird et al., 2015; Johnson-Laird & Byrne, 2002; Johnson-Laird & Khemlani, 2013), a complex statement may have more than one mental model. The conditional *if A, then C* is true only if all its three fully explicit models, AC, ¬AC, ¬A¬C, are possible, but A¬C is impossible (Johnson-Laird et al., 2015). However, the two models ¬AC and ¬A¬C are only implicitly represented, and they can be made explicit only through a demanding and time-consuming fleshing-out process, under some special situation, such as Modus Tollens. In a typical interpretational process,

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the conditional *if A, then C* has only one mental model AC (Johnson-Laird et al., 2015), which is the same as the conjunction *A and C,* together with a footnote implying that other possibilities are possible. On the mental model theory, all mental models are homogeneous regardless of the specific statements involved. Statements therefore should be distinguished from each other via the number of mental models they generated, rather than the quality/properties of the mental models.

Different from the mental model theory, the suppositional theory (e.g. Baratgin et al., 2015; Evans, 2002, 2006; Evans & Over, 2004; Evans, Over, & Handley, 2005) assumes that only one possibility is considered at one time, and this possibility should be the most relevant one (generally the most plausible or probable one) in the current context. Other possibilities will not be considered unless the current possibility is falsified. On this account, statements should be distinguished from each other via the quality/properties of the mental models, rather than the number of mental models involved. To explain the property of the conditional, they hypothesised that the mental model AC constructed from the conditional *if A, then C* involves a hypothetical state of affairs. In understanding the conditional, comprehenders hypothetically add A to their current stock of knowledge and, on that basis, derive inferences about the truth of C (Ramsey, 1929). Unlike the conditional, the same mental model *AC* that is constructed from the conjunction *A and C* involves an actual state of affairs.

These hypothetical properties of A and C engendered by the conditional were put forward by Russell (1903/2010, 1906). According to Russell, a proposition can either be asserted or merely considered in a given situation. Asserting a proposition implies: there exists a situation where the proposition is true; and the situation is in accordance with the facts in the actual world. In contrast, merely considering the proposition without asserting its truth-value means: there exists a situation where the proposition is true; but the speaker doesn't say or doesn't know whether or not the described situation corresponds to the actual world. There are several linguistic markers in natural language that are used to signify whether an uttered proposition is asserted or merely considered. To be specific, the *because*-statement *because A, C* and the conjunction *A and C* create a linguistic context where the two merged propositions A and C are both asserted. By contrast, the conditional *if A, then C* creates a complementary context where the two propositions A and C are merely considered but not asserted.

Previous experimental studies mainly used participants' overt behavioural responses to infer the meaning of conditionals. Truth-table task is a widely used task, where participants are either asked to determine the truth-value of the conditional *if A, then C*, given that one or more of the four models AC, ¬AC, ¬A¬C, A¬C actually happened (i.e. reasoning about truth-values), or asked to determine whether the four models are possible to occur supposing that the conditional is true in the current situation (i.e. reasoning about possibilities) (Barrouillet, Gauffroy, & Lecas, 2008; Gauffroy & Barrouillet, 2009, 2011). The conditional reasoning task and the Wason selection task are also used in previous research to investigate the meaning of conditionals. In the conditional reasoning task, participants are asked to judge the truth value of C, A, ¬C, or ¬A, given the major premise *if A, then C* as well as one of the categorical premises: A, C, ¬A or ¬C are true (such as, Nickerson, 2015). In the Wason selection task (Wason, 1966), participants are asked to make a decision about which cards to flip in order to determine the truth value of the given conditionals. The major findings were that participants' overt behavioural responses varied depending on the specific instructions used in the experiments. More specifically, it was found that the participants didn't consider the two models ¬AC, ¬A¬C as relevant when determining the truth of the conditional *if A, then C* (Evans, Handley, Neilens, & Over, 2007, 2008; Evans, Neilens, Handley, & Over, 2008; Gauffroy & Barrouillet, 2009; Prado & Noveck, 2006), but the participants believed that the same two models ¬AC, ¬A¬C were likely to happen when given the truth of the same conditional (Barrouillet & Lecas, 1998; Schroyens, 2010a, 2010b; Schroyens & Braem, 2010; Schroyens, Schaeken, & Dieussaert, 2008; Sevenants, Schroyens, Dieussaert, Schaeken, & d'Ydewalle, 2008).

To summarise, the mental model theory and the suppositional theory have originally been developed to explain the comprehension of conditional statements in human language and its relation to the meaning of conditionals as defined in classical logic (such as, Evans & Over, 2004). This relation will then be used to evaluate the adequacy of a proposed model of human rationality (such as, Elqayam & Evans, 2011; Evans, 2002). However, the experimental evidence used to adjudicate between these different theories has mainly relied on participants' behavioural responses on complex reasoning tasks. Participants' behavioural responses on these tasks have been found to be substantially affected by several other peripheral factors, such as the specific instructions used, the context of the tasks (such as, Evans & Over, 2004), and participants' individual differences, such as working memory (De Neys, Schaeken, & d'Ydewalle, 2005a, 2005b) etc. So, to gain a better understanding of the meanings of conditionals, we need to reduce the complexity of experimental tasks as well as to control for the peripheral factors that might affect participants' behavioural responses. In the present studies, we aimed to address these issues by recording participants' eye movements, rather than their overt behavioural responses, as the index of how participants comprehended conditional statements.

In our studies, the participants' eye-movements on a concurred image were recorded as they were listening to an auditorily presented statement (Cooper, 1974; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). Several facts revealed in the literature have proven that this paradigm is a powerful tool to explore online sentence processing. First, the eye movements observed in the visual world are largely automatic and task-free (Altmann & Kamide, 2007; but see, Salverda, Brown, & Tanenhaus, 2011). Second, participants tend to fixate more on the object that has not been but possibly will be mentioned. For example, if a cake is the only edible object in the concurrent image, then hearing the sentential fragment *the boy will eat …* would make participants fixate more on the cake (Altmann & Kamide, 1999).

In addition, Zhan, Crain, and Zhou (2015) and Zhan (2018) successfully extended this paradigm to the study of sentential connectives. For example, Zhan et al. (2015) found that participants could use the meaning of sentential connectives to anticipate the propositions that are eligible to be merged. In their study, the participants were auditorily presented with *even if A, C* or *only if A C* while they were watching an image consisting of different *A*s and *C*s. There were two major findings. First, hearing the connective *only if …* triggered more fixations on the *C*s that created two mental models: AC and ¬A¬C; whereas hearing the connective *even if …* triggered more fixations on the *C*s that created two different mental models: AC and ¬AC. Second, the sentential fragment *only if A …* triggered more fixations on the mental model ¬A¬C, because ¬A¬C is the second mental model of the *only if A C*; and the sentential segment *even if A …* triggered more fixations on the mental model ¬AC, because ¬AC is the second mental model of the *even if A C*. These findings suggest that objects that haven't been and won't be mentioned are also more fixated if the objects are relevant to the meaning of the sentence. Similarly, Höhle, Berger, Müller, Schmitz, and Weissenborn (2009) observed that the sentence *the boy also has a doll* triggered more fixations than the sentence *the boy has a doll* on the girl who also had a doll, because the adverb *also* implied that the other person in the concurrent image had a doll, too. To summarise, the visual world paradigm is a temporal sensitive technique that can be used to explore the meaning of both simple propositions and complex statements.

Using the visual world paradigm, this paper reported three eye-tracking studies to explore the meaning of conditionals, by comparing the online interpretation of the conditional *if A, then C* and the conjunction *A and C*. As discussed earlier, the mental model theory and the suppositional theory use different methods to distinguish a conditional from a conjunction. First, the mental model theory assumes that all mental models are homogeneous regardless of the specific statements involved. Statements therefore should be distinguished from each other via the number of mental models they generated, rather than the quality difference between the mental models. Second, the suppositional theory posits that only one mental model is constructed from a statement at one time, so statements should be distinguished from each other via the quality distinction between the mental models, rather than the number of mental models. To be specific, a mental model generated from a statement typically involves the actual situation where a statement is true. A mental model generated from a conditional, however, is only a hypothetical possibility where the statement is true, not the actual situation. To determine which factor is actually used to discriminate between conditionals and conjunctions, we controlled one variable and manipulated the other in the experiments, to see how participants' comprehensions were affected by these manipulations.

In addition, our studies attempted to explore the logical relation between conjunctions and conditionals in human language. A conjunction simply means that the merged propositions are all true. Conjunctive operation is the default compositional operation when two or more simple propositions are merged together, if the operation is not defined otherwise. So a complex statement that merges two or more conjuncts is by default understood as a conjunction. In this sense, there exist plenty of linguistic markers in each human language expressing a meaning of "conjunction", such as *not only A, but also C*; *because A, C*; *A then C*; *A and C* etc. These conjunctions are the same in the core semantics, which is essentially equivalent to the meaning of conjunctions as defined in classical logic. Nevertheless, there also exist several pragmatic differences between these conjunctions. For example, a statement that begins with not only / both / because will be recognised as a conjunction as early as from the onset of these words, while a statement without these markers, such as *A then C*, and *A and C* will not be regarded as a conjunction until the onset of then/and. Furthermore, the two statements *because A, C* and *A then C* will be regarded as engendering a causal relation between A and C, but not the statements *not only A, but also C* or *A and C*. Regardless of these differences, an uttered proposition A will be automatically regarded as asserted rather than as merely considered, as long as the proposition A is not preceded by the conditional connective *if*. So it is secure to use different versions of the conjunctions as the control of conditionals. The main criterion for our choice of a specific version of the conjunction is their naturalness to be uttered in our experimental setting.

We also wish to note that the discussed semantic relation between conditionals and conjunctions should be the same across languages. However, this universal relation might be obscured by the tense relation between the two merged propositions in tensed languages like English. In tensed languages, the two merged propositions in a conditional statement can have different tense forms, resulting in different meanings (such as, Dudman, 1994). When the two merged propositions are both in present tense, such as *if the animal is a goldfish, then it has a goldfish*, this so-called indicative conditional means that the speaker is not in a position to assert the truth of the two merged propositions. When the two merged propositions are in past or past perfect tense, such as *if the animal was a goldfish, then it would have a goldfish*, this so-called counterfactual conditional means that the speaker knows that the animal was not a goldfish, and it didn't have a goldfish. In languages lacking tense, such as Mandarin Chinese (Lin, 2006), whether a conditional is indicative or subjunctive depends largely on the information obtained from the context, rather than on the morphosyntactic markers implemented in the sentence. In the present studies, we used Mandarin as the testing language to control for the tense effect on the interpretation of conditionals.

Experiment 1

Stimuli and design

Experiment 1 explored whether or not the number of mental models could be used to differentiate a conditional from a conjunction, by controlling for the quality/properties of the mental models. Each trial consisted of two simple propositions that were possibly merged as the first component of the complex statement, i.e. two As: A_1 and A_2, such as (4a-b). It was also comprised of three simple propositions that were possibly merged as the second component of the complex statement, i.e. three Cs: C_1, C_2, and C_3, such as (5a-c). We then created four possible situations that merged the five simple propositions in different ways, i.e. A_1C_1, A_1C_1, A_2C_2, A_2C_3, such as (6a-d). Given this experimental setup, there exist two tokens that can be merged as the first component of the statement, i.e. A_1 or A_2. For the conjunction, *A and C*, the two tokens are both possibly eligible, depending on the appropriate choice of C. For the conditional, however, only one of the As, i.e. A_1, is the eligible token for its antecedent. To be specific, if A_2 is chosen as the antecedent, i.e. *if* A_2*, then* C_2/C_3, then no matter which C is chosen as the consequent, there always exists a situation A¬C that falsifies that conditional. On the contrary, if A_1 is chosen as the antecedent, i.e. *if* A_1*, then* C_1, then regardless of which C is chosen as the consequent, the possibility A¬C never exists.

(4)
  (a) A_1: *The animal is a goldfish*.
  (b) A_2: *The animal is a swan*.
(5) Three tokens of the second component (Cs)
  (a) C_1: *The animal has a banana*.
  (b) C_2: *The animal has a feather*.
  (c) C_3: *The animal has a strawberry.*
(6) Four possibilities
  (a) A_1C_1: The first goldfish has a banana.
  (b) A_1C_1: The second goldfish also has a banana.
  (c) A_2C_2: The first swan has a feather.
  (d) A_2C_3: The second swan has a strawberry.

In the experiment, the four possibilities were represented in the four quadrants of the test image, such as Figure 1. And the auditorily presented test sentences were either a conditional *if A, then C* such as (7b) or a conjunction *A and C* such as (7a).

(7) Test sentences
  (a) *Both the animal is a goldfish, and it has a banana*.
  (b) *If the animal is a goldfish, then it has a banana.*

In this experimental setting, the mental model theory and the suppositional theory will make different predictions. According to the mental model theory, a conditional can be represented in two possible ways. On

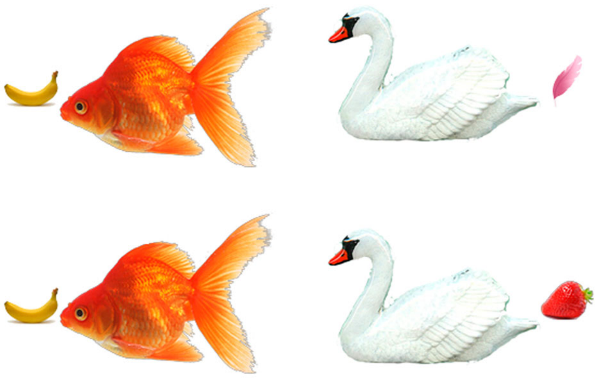

Figure 1. A test image used in Experiment 1.

the one hand, if a conditional *if A, then C* is represented by fully explicit models, then the impossibility of A¬C will be automatically engendered by the conditional, so hearing the conditional connective *if … then …* will automatically make participants realise that the antecedent is A_1 but not A_2. This will trigger more fixations on A_1, rather than A_2, i.e. more fixations on the two goldfishes. On the other hand, if the conditional *if A, then C* is represented by the mental models as well as the footnotes, then the sentential fragment *if A_1, then …* will elicit more fixations on other possibilities besides the mental model, such as ¬A¬C. Therefore, hearing the sentential fragment *if A_1, then …* will elicit more fixations on A_2C_2 and A_2C_3, i.e. more fixations on the two swans.

By contrast, the suppositional theory will make two different predictions. On one hand, the four possibilities created in the test image are all actually true, so the property of the mental model generated from the conditional, *hypothetical*, has no usage in anticipating the proposition being merged. Thus no difference will be elicited by the conditional sentential connective *if … then …* On the other hand, on this account only one mental model is created at a time and hearing the conditional fragment *if A …* will encourage the participants to focus on situations where the antecedent A is true, so the possibilities in which the antecedent A is false will be less activated. In this case, hearing the sentential fragment *if A_1, then …* should trigger fewer fixations on the possibilities A_2C_2 and A_2C_3.

90 images like Figure 1 were created from 45 different animals and 45 different objects. The spatial locations of the animals were counterbalanced throughout different images. 18 conjunctions like (7a) were created from 18 test images, and 18 conditionals like (7b) were created from other 18 test images. The remaining 54 test images and corresponding test sentences were used for a different study that was not reported here. Two trials from each of the 18 trials in each condition were chosen as practices. The remaining 16 trials were used as experimental trials.

The test sentences were recorded by a female native Mandarin-speaker from Beijing. The test audios were recorded word by word and were then combined together, to make the different versions of the test sentences exactly the same except for the sentential connectives. We did a pilot test by asking several native Mandarin-speakers to judge the naturalness of the test sentences in Mandarin, all the interviewees judged the test sentences to be natural Mandarin sentences. The length of the test audios was marked on Figure 2. Figure 2 is only used for illustration purposes, because only one test sentence was created corresponding to each test image. The objects of the second conjunct of the test statements were also counterbalanced, to make the test sentence either true or false with regard to the test images.

Participants

Forty-five students from the Beijing Language and Culture University took part in the experiment. All the participants were native speakers of Mandarin Chinese and had normal or corrected normal visions. They were paid 30CNY (approximately $5) for their participation.

Procedure

Participants were seated approximately 64 cm from a 21 inch, 4:3 colour monitor with 1024*768 pixel resolution. 27 pixels equalled approximately to 1° of visual angle. The sampling rate of the Eyelink II eye-tracker (SR Research Ltd, 2012) was 500 Hz. Viewing was binocular, but only the participant's dominant eye was tracked. Participants were instructed to avoid strong head movements throughout the experiment. The auditory stimuli were presented via a pair of external speakers situated to the left and right of the monitor. The recordings were played from the hard disk as 24 khz mono sound clips. Stimulus presentation and data recording were controlled by two PCs running software developed by SR research Ltd. The keyboard of data presentation PC was used to record participants' button responses.

Participants first saw a brief introduction of the experiment in Mandarin Chinese on the screen, which described the experimental aim, the procedure, and participants' task as we explained below. After the participant was comfortable with the experimental aim, the procedure and the task, the experimenter helped the participant to wear the eye-tracker and performed the standard Eyelink calibration routine. The routine involved participants looking at a grid of five fixation targets in random succession. Then a validation routine followed to test the accuracy of the calibration against the same targets. If the average error of validation was bigger than 1°, the routine was repeated. This routine was conducted at the beginning of each block and whenever the experimenter noticed that measurement accuracy was poor (e.g. after strong head movements or a change in the participant's posture).

A typical trial started by presenting a black dot at the centre of the screen. The participant was instructed to press the SPACE key while fixating on the dot. The press brought up the test image. 200 ms after the onset of the test image, the test sentence began to play. Participants were instructed to view test images and to listen to the sentences attentively, so that they could judge a). **And**

不但	这个动物	是一个	金鱼,	它	还	有一个	香蕉/* 羽毛
budan	zhege dongwu	shi yige	jinyu	ta	hai	you yige	xiangjiao/*yumao
not only	this animal	is a	goldfish	it	also	has a	banana/*feather

*The animal is a swan, and it has a banana/*feather.*

b). **If**

如果	这个动物	是一个	金鱼,	它	就	有一个	香蕉/* 羽毛
ruguo	zhege dongwu	shi yige	jinyu	ta	jiu	you yige	xiangjiao/*yumao
if	this animal	is a	goldfish	it	then	has a	banana/*feather

*If the animal is a goldfish, then it has a banana/*feather.*

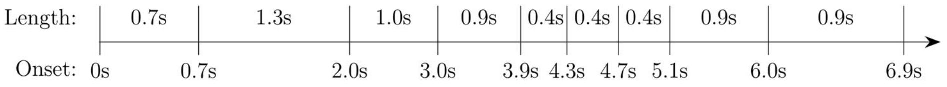

Figure 2. A set of auditorily presented sentences corresponding to Figure 1, which were used in Experiment 1. The sentences marked with asterisks are the ones that are inappropriate to utter given the test image.

Note: This is only for the purpose of illustration, as in the real experiment only one sentence was created corresponding to each test image.

whether or not it was appropriate to utter the test sentence in the situation constructed from the test image. If the answer was appropriate, left arrow key should be pressed, and if the answer was inappropriate, the right arrow key should be pressed. Participants' eye movements were recorded from the onset of the test image to the offset of the trial. Pressing a key or 10,000 ms after the offset of the test audio brought out a new trial.

Data processing

To analyze the eye movement data, we first categorically partitioned the temporal period from the onset of the test image to the offset of the test audio into 70 temporal bins, 100 ms long each. We then divided the test image into two areas of interest: the first area covered the two mentioned animals, and the second area covered the two unmentioned animals. The proportion of fixations on a particular area in a specific temporal bin was chosen as the dependent variable. For example, if we recorded 4 fixation points in a temporal bin, with 1 fixation point locating in a specific area, then the proportion of fixations on that area was ¼. Fixations shorter than 80ms were pooled with preceding or following fixations if they were within 0.5° of visual angle, otherwise they were deleted.

To report the data, we first produced a descriptive diagram of participants' proportions of fixations. We then transformed the fixation proportions with the following empirical logit formula (Barr, 2008): $probability = \ln((y + 0.5)/(n - y + 0.5))$, where y is the number of fixations on the interested areas during a particular temporal bin; n is the total number of fixations in that temporal bin.

We then fitted a series of generalised linear mixed-effects models to the transformed data. In the full model, the fixed effects include the temporal bin, the sentential connectives, and their interactions; the random effects include items and participants, where both their intercepts and slopes were allowed to vary among all the fixed effects and the fixed effects' interactions (Baayen, Davidson, & Bates, 2008; Barr, Levy, Scheepers, & Tily, 2013). We then reduced the full model's complexity to see whether the reduced model could explain the same variance as the full model (Bates, Kliegl, Vasishth, & Baayen, 2015). If it could, we would accept the simplified model. The final model we used could be found in the footnote of the tables reporting the statistical results. Analyses were carried out on the raw data with no aggregation. When conducting the analysis, the temporal bins were rescaled and grand-mean centred, to avoid issues involving collinearity. We conducted the fitting process via functions *lmer* from package *lme4* (v1.1–12) (Bates, Maechler, & Bolker, 2013) of the R (v3.2.5) software environment (R Development Core Teem, 2010). We then used Wald test to get the *p*-values for each fixed effect.

Results

The proportion of trials on which participants provided correct behavioural responses was significantly higher than the chance level (Proportion = 0.5) both in the conjunctive condition (Proportion = 92.6%, χ^2 (1) = 521.9, $p < 0.001$) and in the conditional condition (Proportion = 97.9%, χ^2 (1) = 659.3, $p < 0.001$). These high proportions indicated that participants paid enough attention to our experimental setting, and thus established a basis for us to deduce a valid conclusion from participants' eye movements. To explore whether there is a significant difference between the two conditions, we conducted a generalised linear mixed effect model (GLMM) with the sentential connective as the fixed effect. The random effects of the model include both the intercept and the slope of the sentential connective with respect to the participants as well as with respect to the trials. No significant difference was observed between the two conditions ($\beta = -0.06$, $p = .30$).

As participants' fixation patterns in the two areas were complementary to each other, we only reported participants' fixations on the unmentioned animals. The results are shown in Figure 3. As shown in the figure, the fixation patterns between the conjunction and the conditional are almost the same until the onset of the second merged proposition. In the second proposition, the conditional triggered significantly fewer fixations on the unmentioned animals, as compared to the conjunction.

To validate these three observations, we divided the whole 70 temporal bins into three temporal periods. It is generally acknowledged that mentioning an object would elicit more fixations on the token of that object. To explore the effects of the sentential connectives rather than the effects of mentioning an object, we intentionally excluded the temporal period where the interested objects were mentioned. More specifically, the first temporal period ranged from the onset of the test image to the onset of the test audio; the second temporal period ranged from the onset of the test audio to the onset of the object of the first proposition, i.e. *if/both the animal is a … .*; and the third temporal period ranged from the onset of the second proposition to the onset of the object of the second proposition, i.e. *then/and the animal has a …* We then fitted a mixed model to each of the three temporal periods. The independent variable of the experiment was the type of sentential connectives that had two levels: *and* and *if*. When conducting the statistical analysis, we treated the sentential connective *and* as the reference level. The main effect labelled as *if* denoted the difference between the sentential connectives *if* and *and*.

The fitting results are summarised in Table 1. In the first temporal period, no difference between the conditional and conjunction condition was observed ($\beta = -0.01$, $p = .90$), validating the baseline that there was no systemic difference between the basic visual properties of the unmentioned animals in the two conditions. In the second temporal period, no difference

Table 1. Fixed effects of the models fitted to participants' fixation patterns on unmentioned animal in experiment 1.

Temporal period	Fixed effects	*β*	*SE*	*t*	*p*	sig
Pre-Audio Onset	(Intercept)	−0.98	0.05	−20.74	0.00	***
	Temporal bin	−0.01	0.03	−0.30	0.77	
	If	−0.01	0.07	−0.12	0.90	
	Bin:*If*	0.00	0.04	0.07	0.95	
If/both the animal is …	(Intercept)	−1.08	0.05	−20.57	0.00	***
	Temporal bin	−0.07	0.02	−2.75	0.01	**
	IF	0.07	0.07	1.00	0.32	
	Bin:*IF*	0.02	0.03	0.68	0.50	
then/and the animal has a …	(Intercept)	−1.84	0.07	−25.20	0.00	***
	Bin	−0.02	0.02	−0.88	0.38	
	IF	−0.11	0.05	−2.23	0.03	*
	Bin:*IF*	0.01	0.02	0.63	0.53	

Note: Formula used in R: Probability ∼ 1 + Temporal bin * Connective + (1 + Temporal bin * Connective | subject) + (1 + Temporal bin * Connective | item).

Significant level: ***$p < .001$, **$p < .01$, *$p < .05$

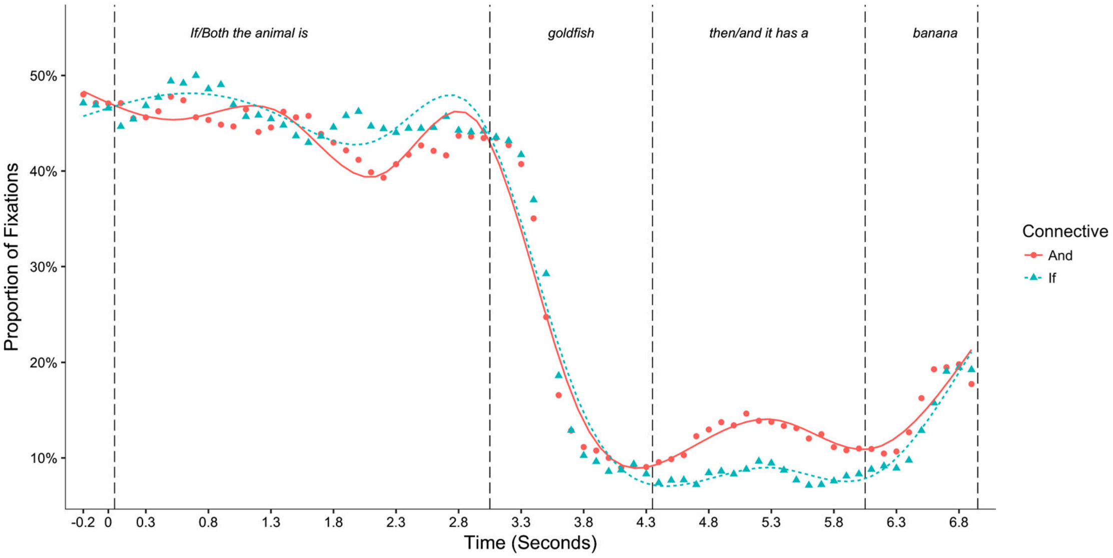

Figure 3. Fixation patterns on the unmentioned animals, such as the two swans in Figure 1.

between the two sentential connectives *both … and …* and *if … then …* was observed ($\beta = 0.07$, $p = .32$), indicating that the conditional connective *if* was not used to make anticipatory eye movements. In the third temporal period, however, a significant effect was recorded, but in a way deviating from the prediction of the mental model theory. To be specific, the unmentioned animals, i.e. the mental models ¬AC and ¬A¬C, were significantly less fixated when the sentential connective was *if … then …* than when it was *and* ($\beta = -0.11$, $p = .03$).

Experiment 2

These effects observed in Experiment 1 are contradictory to the mental model theory, as neither of the predictions made by the mental model theory was confirmed in Experiment 1: the conditional connective did not elicit anticipatory eye movements to the animals that were going to be mentioned; and the unmentioned animals were less fixated, rather than more fixated when the sentential connective was *if … then …* .

The observed effects, however, are compatible with the suppositional theory. According to the suppositional theory, only one mental model is considered at a time, regardless of what the statement is. A conditional differs from other statements in the quality/properties of the generated mental models, rather than in the number of the generated mental models. A typical mental model describes a possibility where the statement is actually true in the current situation, whereas the mental model engendered by a conditional is only hypothetically true in the situation. All the mental models created in Experiment 1, however, were actually true in the supposed situation. So according to the suppositional theory, the mental models created in Experiment 1 should not be differentiated by the conditionals. Nevertheless, this reasonable explanation might be confounded by a further possibility: this negative result observed in Experiment 1 was simply due to that the visual world paradigm is not sensitive enough to record the effects elicited by conditional connectives. Experiment 2 was then designed to exclude this possibility and to verify the validity of the suppositional theory. To be specific, Experiment 2 explored whether or not the manipulated property of the mental models can be used to differentiate conditionals from conjunctions, by controlling for the number of the mental models.

Stimuli and design

Experiment 2 created two propositions that are possible to be merged as the first component of the complex statement, i.e. two As: A_1, and A_2 (8a-b), and one proposition that is possible to be merged as the second component of the complex statement, i.e. C (9a). Six auditory Mandarin sentences were recorded as test sentences, corresponding to the test image (Figure 4). The six test sentences were exactly the same, except for the three sentential connectives (i.e. *and, because*, and *if*) and the

a). **And**

你看	公主	吃掉了	那个	苹果	/*香蕉	之后	她	就会受到惩罚
nikan	gongzhu	chidiaole	nage	pingguo	/*xiangjiao	zhihou	ta	jiu hui shoudao chengfa
look	princess	eat-Asp	that	apple	/*banana	then	she	will be punished

*Look, the princess eats that apple/*banana, then she will be punished.*

b). **Because**

因为	公主	吃掉了	那个	苹果	/*香蕉	所以	她	就会受到惩罚
yinwei	gongzhu	chidiaole	nage	pingguo	/*xiangjiao	suoyi	ta	jiu hui shoudao chengfa
because	princess	eat-Asp	that	apple	/*banana	therefore	she	will be punished

*Because the princess eats that apple/*banana, therefore she will be punished.*

c). **If**

如果	公主	吃掉了	那个	*苹果	/香蕉	那么	她	就会受到惩罚
ruguo	gongzhu	chidiaole	nage	*pingguo	/xiangjiao	name	ta	jiu hui shoudao chengfa
if	princess	eat-Asp	that	*apple	/banana	then	she	will be punished

*If the princess eats that *apple/banana, then she will be punished.*

Length:	0.95s	0.95s	1.2s	0.9s	1.1s	(1.1s)	0.9s	0.4s	1.2s
Onset:	0s	0.95s	1.9s	3.1s	4.0s	4.0s	5.1s	6.0s	6.4s	7.6s

Figure 4. A set of auditorily presented sentences used in Experiment 2 and Experiment 3. The sentences marked with asterisks were the ones that were inappropriate to utter given the test image.

object of the antecedent A, such as *apple* and *banana*, resulting in a 3 by 2 experimental design. Even though it was logically equivalent to the conjunction, the *and* condition used in this experiment didn't contain any sentential connectives. This conditional was originally designed as filler items of this experiment, but it turned out that comparing this condition with other two conditions was also interesting.

(8) Two tokens of the first component (As)
  (a) A_1: *The princess eats an apple.*
  (b) A_2: *The princess eats a banana*.
(9) The consequent (C)
  (a) *The princess will be punished*.

The test image corresponding to (8–9) encompassed a person (e.g. a princess) and two objects such as an eaten apple and an intact banana (see Figure 5). Given this test image, there existed a crucial difference between the two As: the A_1 is actually true in the created situation, i.e. the apple has already been eaten in the experimental setting; while the A_2 is only possibly or hypothetically true in the created situation, i.e. the banana is edible but has not been eaten in the experimental setting. Furthermore, the truth of the second component C is unavailable to participants, i.e. the participants don't know whether the princess is actually punished or not.

In this experimental setting, the suppositional theory and the mental model theory will also make different predictions. On the one hand, the suppositional theory assumes that the mental model AC constructed from the conjunction *A and C* is actually true in the current situation, while the same mental model AC constructed from the corresponding conditional *if A, then C* is only hypothetically true, but not actually true in the current situation. In our experimental setting, the first token A_1 is actually true, while the second token A_2 is only hypothetically true. So if the suppositional theory is on the right track, then after hearing the conditional connective *if …* participants will realise that the antecedent being merged is A_2, instead of A_1, leading to more fixations on A_2 than on A_1. By contrast, on the mental model theory all mental models are homogeneous. Thus, our manipulated quality difference between A_1 and A_2 cannot be utilised to anticipate the appropriate As that will be merged as the antecedent. In addition, the truth-value of the second component C is undetermined, so the impossibility of $A\neg C$ cannot be used to anticipatorily exclude the inappropriate As.

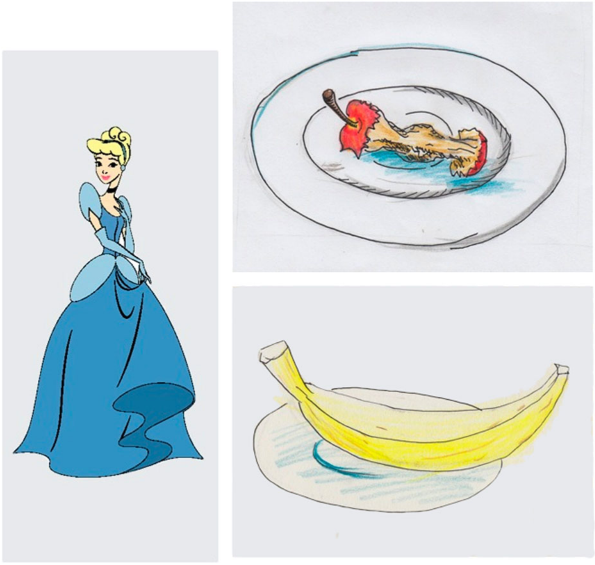

Figure 5. A test image used in Experiment 2 and Experiment 3.

Note: This image is an image that is actually used in Experiment 2. The images used in Experiment 3 have the same layout as the example, but are not exactly the same as the one shown in Figure 5 (see the main text for more discussion).

In terms of the test images and test sentences, the verbs used in the proposition had the following property: the action engendered by the verbs changed the status of the object. For example, the verb *read* would not be an appropriate verb, because *read a book* does not change the status of the book; whereas *tear up* is a good one, because *tear up a book* changes status of the book from a completeness into parts (i.e. pieces of papers). Based on this criterion, 18 Mandarin Chinese verbs were selected. Henceforth, 18 test images like Figure 5 and 18*3*2 = 108 test sentences like Figure 4 were devised. The spatial positions of the person and the two objects were counterbalanced across test images. 4 more images and 4 more sentences were created as practices, resulting in 22 images and 112 trials in total. A female Mandarin-speaker from Beijing was recruited to record the test sentences.

Participants

39 students from the Beijing Language and Culture University participated in the experiment. All the participants were native speakers of Mandarin Chinese, with normal or corrected normal visions. None of the participants had participated in Experiment 1. They were paid 30CNY (approximately $5) for their participation.

Procedure, and data preprocessing

The experimental procedure and data processing were the same as in Experiment 1.

Results

Participants' behavioural responses were significantly higher than the chance level in all the three conditions (*And* condition, Proportion = 79.34%, χ^2 (1) = 482.43, $p < 0.001$; *Because* condition, Proportion = 96.94%, χ^2 (1) = 1235.40, $p < 0.001$; and *IF* condition, Proportion = 81.20%, χ^2 (1) = 545.32, $p < 0.001$), indicating that participants paid enough attention to our experimental setting. This serves as the basis for us to deduce a valid conclusion from participants' eye movements. The GLMM analysis revealed that the rates of correctness were significantly higher when the sentential connective was *Because* than the baseline conditions ($\beta = 0.25$, $p < .001$), and no significant difference was found between the *IF* condition and the baseline condition ($\beta = 0.06$, $p = .42$). This suggests that the statements connected by *Because* are easier to be comprehended than that are connected by the conditional connective, *If*.

Experiments 2 attempted to examine whether or not the conditional connective could be used to make anticipatory eye-movements, supposing that the truth-value of the consequent was unknown. The temporal period we analysed ranged from the onset of the test audio to the onset of the object of the antecedent, excluding the information of both the antecedent and the consequent. Figure 6 summarised participants' proportion of fixations on the factual possibility (top left panel, i.e. the eaten apple in the example image) and on the hypothetical possibility (top right panel, i.e. the intact banana in the example image) during this temporal period. As indicated in the figure, the eaten apple was more fixated when the sentential connective was *because*; and the intact banana was more fixated when the sentential connective was *if*. The effects occurred before the onset of the object of the antecedent.

To assess the statistical significance of the observed differences, we fitted a series of models to the two areas of interest respectively. In these models, the independent variable was the type of sentential connectives that had three levels: *and*, *because*, and *if*. When reporting the results, we used *and* as the reference level. A main effect denoted a difference between a sentential connective and the reference level in the intercepts of the two fitted lines. An interaction denoted the difference in the slope of the fitted lines.

The results of Experiment 2 are summarised in the upper parts of Table 2. First, the sentential connective *if* triggered significantly less fixations on the factual possibility (i.e. the eaten apple in the example image) than the reference level *and* ($\beta = -0.05$, $p = .05$), and no main effect was observed between *because* and *and*. Interactions between the effects of sentential connective and the temporal bin are observed both in *if* condition and in *because* condition, but in the opposite direction. More specifically, the sentential connective *because* triggered more and more fixations on the factual possibility than the reference level *and* as the temporal bin became bigger ($\beta = 0.02$, $p = .00$). In contrast, the sentential

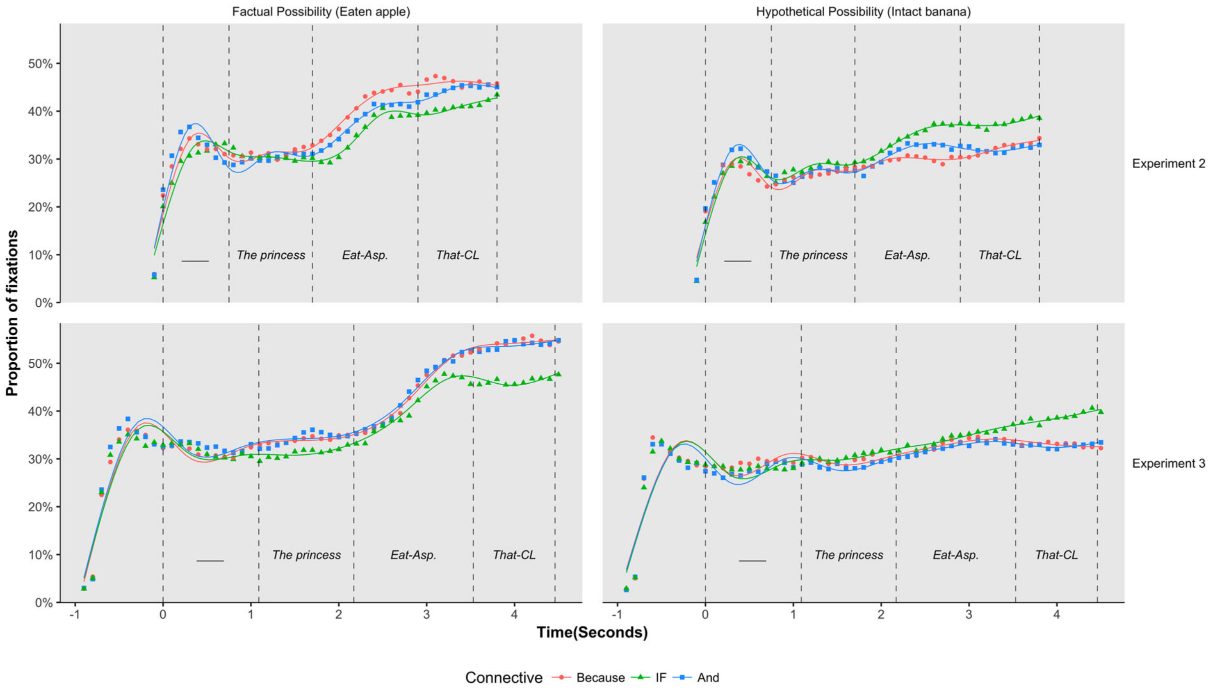

Figure 6. Participants' fixation patterns on actual possibility (left panels) and on the hypothetical possibility (right panels) in Experiment 2 (top panels) and in Experiment 3 (bottom panels).

Table 2. Fixed effects of the models fitted to participants' fixation patterns on the factual possibility and on the hypothetical possibility in Experiments 2 and 3.

	Factual possibility					Hypothetical possibility				
Fixed effects	*β*	*SE*	*t*	*p*	sig	*β*	*SE*	*t*	*p*	sig
Exp 2										
(Intercept)	−0.25	0.06	−4.19	0.00	***	−0.41	0.07	−5.48	0.00	***
Bin	0.14	0.02	6.63	0.00	***	0.06	0.02	3.40	0.00	***
Because	0.03	0.02	1.21	0.23		−0.02	0.02	−1.04	0.30	
IF	−0.05	0.02	−1.99	0.05	*	0.05	0.02	2.73	0.01	**
Bin:*Because*	0.02	0.01	3.18	0.00	**	0.00	0.01	0.36	0.72	
Bin:*IF*	−0.02	0.01	−3.11	0.00	**	0.06	0.01	9.38	0.00	***
Exp 3										
(Intercept)	−0.85	0.12	−7.03	0.00	***	−1.67	0.11	−14.52	0.00	***
Bin	0.66	0.08	8.77	0.00	***	0.19	0.06	3.22	0.00	**
Because	−0.04	0.08	−0.55	0.58		0.06	0.06	1.04	0.30	
IF	−0.27	0.09	−3.12	0.00	**	0.19	0.09	2.03	0.04	*
Bin:*Because*	0.02	0.06	0.33	0.74		−0.03	0.06	−0.52	0.60	
Bin:*IF*	−0.16	0.07	−2.19	0.03	*	0.12	0.06	2.09	0.04	*

Note: Formula used in R: Probability ∼ 1 + Temporal bin * Connective + (1 + Temporal bin * Connective | subject) + (1 + Temporal bin * Connective | item).
Significant level: ***$p < .001$, **$p < .01$, *$p < .05$

connective *if* triggered fewer and fewer fixations on the factual possibility than the reference level *and* as the temporal bin became bigger ($\beta = -0.02$, $p = .00$). Second, the sentential connective *if* triggered significantly more fixations on the hypothetical possibility (i.e. the intact banana in the example image) than the reference level *and* ($\beta = 0.05$, $p = .01$), and no main difference was observed between *because* and *and*. An interaction between the sentential connective and the temporal bin also existed in the conditional connective *if* ($\beta = 0.06$, $p = .00$), but not in the sentential connective *because*. To be specific, the conditional connective *if* triggered more and more fixations on the hypothetical possibility as the temporal bin became bigger.

To summarise, the conditional connective *if …* elicited more fixations on the hypothetical possibility, whereas the sentential connective *because* and *and* both elicited more fixations on the factual possibility. The difference between *because* and *and* is only shown in their interaction with the temporal bins, suggesting that both *and* and *because* statements involved a factual possibility.

Experiment 3

In Experiment 2, the same test image was presented to the same participant six times, accompanied by six different test audios. This experimental design might cause a potential confounding that the participants might be getting accustomed to the test stimuli and possibly even becoming strategic about how they have responded to the test stimuli. The addition of Experiment 3 is a response to a reviewer's comment that the repetition of the test items in Experiment 2 poses the concern that the participants might be getting accustomed to these stimuli and possibly even becoming strategic about how they have responded to the stimuli.

Stimuli and design

In Experiment 3, we created three objects that could be used as the object of each verb. A test image could comprise of any two of the three objects, and an object shown in a test image could either be true or false. This experimental design resulted in six test images corresponding to each verb, with the spatial locations of the objects being counterbalanced. 23 verbs, 23 agents (the subjects of the verbs), 69 objects and 138 test images were created in total. All the test images were drawn by a postgraduate majored in painting. In terms of the test audios, both the sentential connectives and the objects of the verbs were manipulated, leading to six test audios corresponding to each test image and 828 audios in total. A female Mandarin-speaker from Beijing was paid 200CNY to record the test sentences. The audios were then divided into six groups. Each participant saw all the test images but heard only one version of the test audios. 2 verbs, 12 test images and the corresponding 12 test audios were chosen as practices. The remaining 21 verbs, 126 test images and 126 test audios in each group were used as test items in the actual experiment.

Participants

60 participants (10 students in each group) from the Beijing Language and Culture University participated in the experiment. All the participants were native speakers of Mandarin, with normal or corrected normal visions.

None of the participants had participated in Experiment 1 or Experiment 2. They were paid 30CNY (approximately $5) for their participation.

Procedure, and data preprocessing

The experimental procedure and data processing were the same as in Experiment 2, with the following two exceptions. The eye-tracker we used was Eyelink 1000 plus, rather than Eyelink II. To help the participants familiarise with the test image, the ISI between the onset of the test image and the onset of the test audio is 1000 ms, rather than 200 ms.

Results

The GLMM analyses conducted on participants' behavioural responses reveal that the rates of correctness were significantly lower when the sentential connective was *If* than the baseline conditions ($\beta = -0.07$, $p = .02$), and no significant difference exists between the *Because* condition and the baseline condition ($\beta = 0.04$, $p = .28$). Once again, this suggests that the statements connected by *Because* was easier to comprehend than those connected by the conditional connective, *If*.

Participants' eye movements are summarised in the two lower panels of Figure 6. We wish to note that the test audios used in Experiment 2 and Experiment 3 were from two different speakers, and thus the speed of speaking and the durations of the corresponding audio elements are not the same in the two experiments. To make the results observed in Experiment 2 and Experiment 3 more comparable, we time-locked our diagrams to the onset of the test audios. As showed in Figure 6, the fixation patterns observed in Experiment 3 were quite similar to those observed in Experiment 2. The statistical results (Lower parts of Table 2) confirmed this similarity, indicating that the effects observed in Experiment 2 was robust and was not confounded by the repetition of the test stimuli.

Discussion

There were two major observations from the three experiments: (a). Only one mental model is generated from a statement at one time; and (b). The mental model AC engendered by the conditional *if A, then C* is not actually true but rather hypothetically true. The two observations are in accordance with the suppositional theory (Evans, 2006; Evans et al., 2005; Evans & Over, 2004), but are contradictory to the mental model theory.

According to the mental model theory (Johnson-Laird et al., 2015, p. 206), the conditional *if A then C* is true only if all three situations in its fully explicit models AC, ¬AC, ¬A¬C are all possible, and A¬C is impossible. Nevertheless, the mental model theory can also explain these findings if it makes a small modification to accept (a): only one mental model is generated from a statement at one time. If (a) is accepted, then the meaning of the conditional *if A then C* should be rephrased as: the conditional *if A then C* is true in a situation only if its fully explicit models AC, ¬AC, ¬A¬C are all possible, and A¬C is impossible in this situation. Because AC and ¬AC are both possible in the situation, so A could be both possibly true and possibly false in this situation. Since ¬AC, ¬A¬C are both possible in the situation, so C could also be both possibly true and possibly false in the same situation. As a proposition cannot both be true and false in an actual world, so the two propositions A and C have to exist in a nonfactual hypothetical world, i.e. (b): The mental model AC engendered by the conditional *if A, then C* is not actually true but rather hypothetically true.

The hypothetical property of a mental model can actually be generalised to other statements. Given any complex statement, if this statement has two or more fully explicit models and entails that a simple proposition is both possibly true and possibly false, then the model constructed from the simple proposition should be hypothetical. For example, the disjunction *A or C* also has three fully explicit models A¬C, ¬AC, and AC. A¬C and AC entails that C is both possibly true and possibly false in the given situation. ¬AC, and AC entails that A is also both true and false in the situation. Taken together, the disjunction *A or C* entails that A and C are only hypothetical but not actual description of the actual world. Uttering and comprehending a hypothetical description that is not actually true in the current situation is an important property of human language (Hockett, 1960) and human thinking (Evans & Over, 2004). With this property, humans can describe and comprehend the situations that don't, or haven't, or won't experience, or the situations that don't exist.

Dual-process accounts have been widely used to explain human behaviours in reasoning and decision making, as well as in social cognition (e.g. Evans, 2006, 2008, 2010; Evans & Stanovich, 2013; Kahneman, 2011; Oaksford & Hall, 2016): In the two Systems of the accounts, System 1 is unconscious, fast, heuristic, and phylogenetically older; and System 2 is slow, analytic, and conscious, that coevolved with language and working memory. According to the new development of the dual-process theories, System 1 is rational, and the observed irrationality of human reasoning does not come from the system, but comes from the limitations of working memory and language, when the products of System 1 are passed to System 2 or are communicated with others (Oaksford & Hall, 2016). In comparison with the behavioural responses reported in the literature, the eye-tracking technique used in this study bypasses these two limitations of human mind. First, we used the eye movements participants automatically generated rather than the overt behavioural responses participants gave to infer their comprehension of the test sentences. Second, participants' responses were recorded in real time, so that there was no need for them to remember the auditorily presented test sentences or the test images in order to give behavioural responses at the end of each trial. Taken together, the results observed in the present studies are much less distorted by the sources of errors in human reasoning, such as working memory, and language.

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