# Estimating a Time Series of Interpretation Indeterminacy in Reading a Short Story Using a Quantum Cognition Model

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**Abstract**

Literary and aesthetic studies have suggested that readers can stay in indeterminate states where they hold multiple interpretations, and that this indeterminate interpretation state causes an aesthetic feeling, involvement, and understanding of art. To explore the indeterminate interpretation state, we employed a quantum cognition framework and conducted a reading experiment using a short story. The results suggest that readers' interpretations can be regarded as a superposition state corresponding to the indeterminate and polysemous interpretation of the story. We also estimated a time series of quantum indeterminacy and discussed the text features related to quantum indeterminacy.

**Keywords:** comprehension; indeterminacy; interpretation; quantum cognition; superposition state

## Indeterminate Interpretation

While reading, readers can make multiple interpretations of novels. With romantic fiction, they feel that she may love him but may not at the same time. In mystery, they wonder whether person A could be a criminal, but person B is also a candidate. Studies in literature and aesthetics have indicated this indeterminacy of interpretation. Eco (1989) proposed "open works," which indicates room for interpretation, involves audiences or viewers in the arts and causes aesthetic feelings. Iser (1976) also suggested that the reader can hold the undecided interpretation (blank spaces), and this space makes readers involved. These types of polysemous interpretations with indeterminacy lead to emergent interpretations, which cannot be reduced to the composition of each interpretation alone.

In cognitive science and psychology, text comprehension studies have not focused on the polysemous interpretations with emergencies and indeterminacy. Previous studies of comprehension, especially regarding modeling of cognitive processes, have hypothesized that readers choose the most plausible interpretation based on context or their knowledge at any point in time (Gernsbacher, 1997; Kintsch, 1988), and explored how readers choose one interpretation. For explanatory texts, this hypothesis seems reasonable, but for literary texts, it is worth considering according to literary and aesthetic studies.

This study explores indeterminacy in the comprehension of literary texts in a scientific manner using the framework of quantum cognition. Quantum cognition employs the quantum probability theory instead of the classical probability theory to model cognition (Pothos & Busemeyer, 2022; Busemeyer & Bruza, 2012). The polysemous understanding of words or texts has been modeled using the quantum cognition framework (Gabora & Kitto, 2017; Bruza & Woods, 2008; Surov et al., 2021; Fuyama, 2023). A model based the quantum probability theory can represent indeterminate cognitive states that cannot be represented by classical probability theory. We employ the superposition state, which is a specific state represented by quantum probability theory, to model the indeterminate and polysemous interpretations of texts and test our assumption that readers can hold indeterminate states.

Furthermore, we estimate the time series for indeterminacy in text interpretation using $q$ value (Wang, Solloway, Shiffrin, & Busemeyer, 2014) which represents a degree of "quantum nature." Time series estimation enables us to discuss how readers' indeterminacy changes during reading and the characteristics of texts or contexts that lead readers to be indeterminate. We also discuss whether our model can distinguish indeterminacy with multiple interpretations from indeterminacy with no appropriate interpretation. This study explores the former, as indicated by Iser (1976) and Eco (1989). The latter is linked to a lack of appropriate interpretation, such as readers' states at the beginning of reading. This difference is related to previous comprehension models (Gernsbacher, Varner, & Faust, 1990; Fuyama & Hidaka, 2016). We discuss this further in the Discussion section.

For the quantum cognition fields, as a model and the method of analysis, we basically employed the same approach used by Wang et al. (2014) and Fuyama (2023). The main novelties of this study in the field of quantum cognition are applying the prediction of QQ equality to examine literary texts and estimating the time series related to the quantum nature of cognition.

## Model of Indeterminate Interpretation Using Superposition State

In this study, we modeled an indeterminate and polysemous interpretation of a story as a superposition state using quantum probability. For the indeterminate future of quantum cognition, please refer to Pothos and Busemeyer (2022) and Fuyama (2023). We briefly explain the state of superposition and its emergence.

As in the previous studies on quantum cognition (Aerts,



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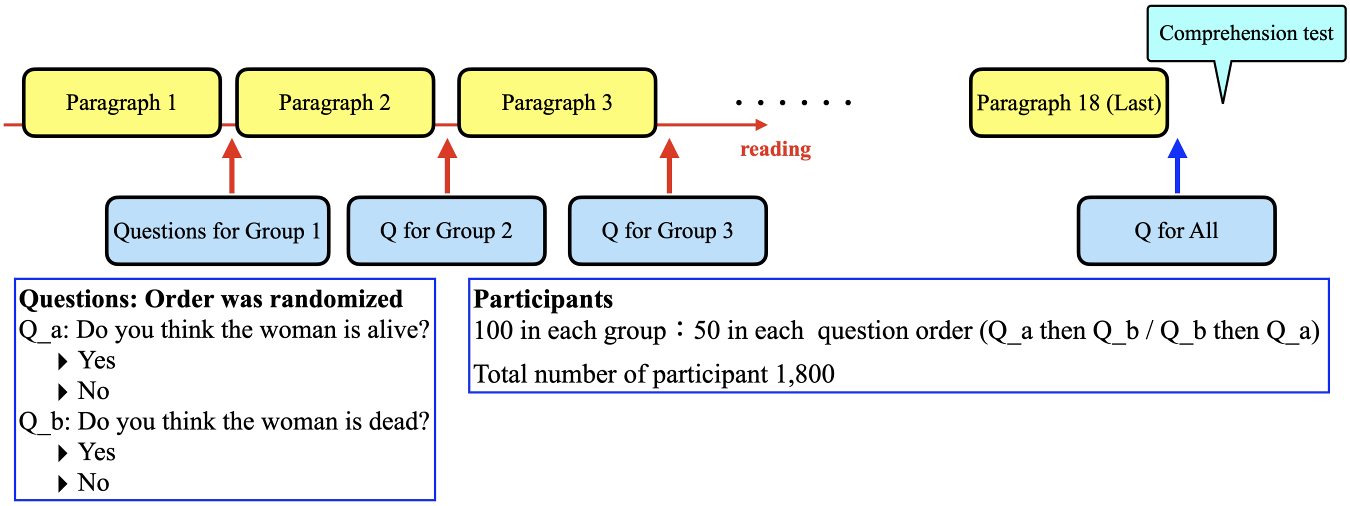



Figure 1: Procedure of the main task.

2009; Busemeyer & Bruza, 2012; Pothos & Busemeyer, 2022), we modeled cognitive state as the state vector $\psi$. The state of interpretation X is represented by $\psi_X$, and interpretation Y is represented by $\psi_Y$. When the reader's interpretation state is in the superposition of interpretations X and Y, we represent this state as $\psi_{whole}$ such that

$$\psi_{whole} = c_1\psi_X + c_2\psi_Y \mid c_1, c_2 \in \mathbb{C}, c_1^2 + c_2^2 = 1 \tag{1}$$

$c_1$ and $C_2$ are not the probability itself, but the probability amplitudes. To measure the states of interpretation, the probability distributions are represented as follows:

$$\begin{aligned} &\langle \psi_{whole} | P(a) | \psi_{whole} \rangle \\ &= |c_1|^2 \langle \psi_X | P(a) | \psi_X \rangle + |c_2|^2 \langle \psi_Y | P(a) | \psi_Y \rangle \\ &\quad + c_1^* c_2 \langle \psi_X | P(a) | \psi_Y \rangle + c_2^* c_1 \langle \psi_Y | P(a) | \psi_X \rangle \end{aligned} \tag{2}$$

$\langle x|$ represents a row vector, and $|x\rangle$ represents a column vector in the Hilbert space based on the bracket notation. $P(a)$ is the projection operator on the vector $a$. In this case, $\langle \psi_{whole} | P(a) | \psi_{whole} \rangle$ denotes the probability that the reader whose state is $\psi_{whole}$ agrees with the interpretation "a" for the story. The $\langle \psi_X | P(a) | \psi_X \rangle$ indicates the probability that the reader whose state is $\psi_X$ agrees with the interpretation "a" for the story. The last two terms of Equation2 are called the "interference term," which characterizes the superposition state and represents the emerged interpretation based on interpretations X and Y. The interference terms cannot be reduced to either one of the two interpretation states of X and Y. This feature represents the emergent and indeterminate state that cannot be settled based on one interpretation. Since classical probability theory cannot represent this interference term, the superposition states are emergent and indeterminate states inherent to the model based on the quantum probability theory.

We used QQ equality (Wang et al., 2014) to test the hypothesis that reader interpretation states can be regarded as a superposition of more than two interpretations (Fuyama, 2023). QQ equality represents the relationship between the size of the order effect caused by the interference term.

In this study, participants read a short story in which a man and a woman are the main characters. We asked the participants two questions: "Do you think the woman is alive?" and "Do you think the woman is dead?" For each question, participants answered either yes or no. Thus, there were four patterns: answering Yes to the alive question and No to the death question.

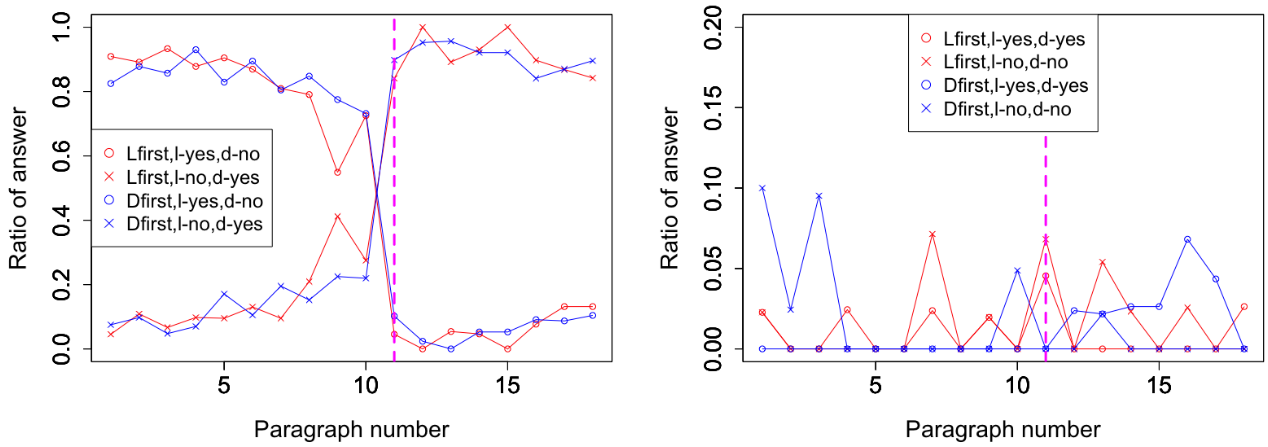
The order of the questions was randomized for each participant (we referred to each order as the alive/death first condition). The size of the order effect was calculated by subtracting the ratio of each answer pattern in the death-first condition from that of the alive-first condition. We represented the size of each order effect as $q_{yy}$, $q_{yn}$, $q_{ny}$, $q_{nn}$. Here, $q_{yn}$ is defined as the difference in the ratio of answering YES to the alive question and NO to the death question in the alive first condition from the same ratio in the death first condition. If the cognitive states are in the superposition state, QQ equality predicts $q\ value = q_{yy} - q_{nn} = q_{yn} - q_{ny} = 0$ . (For more information, see Wang et al. (2014) and Fuyama (2023)).

In everyday conversation, life and death are typically considered antonyms, and it is generally believed that one would not answer "yes" or "no" to both questions. (In other words, within the Wang et al. (2014) framework, life and death are orthogonal in the Hilbert space.) However, in this study, we assumed that situations arise in narrative comprehension where life and death are not necessarily antithetical. We touch on this point in the Materials subsection and discuss it further in the Discussion.

## Experiment

### Material

We employed a Japanese short story named "Dai-ichiya" which is a short story from *Yume-juya* written by Soseki Natsume, a famous Japanese novelist. The story includes 18




(a) Time series for data with different answers to the two questions. (b) Time series for data with same answers to the two questions.

Figure 2: Time series of the ratio of the answer. "Lfirst" means the alive first condition. "Dfirst" means the death first condition. "l-yes, d-no" represents the ratio of yes to alive and no to death questions. "l-no", "d-yes" are interpreted by the same rule.

paragraphs and 68 sentences. The main characters in the story are a man and a woman. In the first half of the story, she tells him that she will die soon and return if he waits for 100 years. Subsequently, she dies. In the second half, he buries her as she asks him and waits. A long time passes, but she does not return. On one day, the lilies grow and bloom. The man kisses the lily and realizes she returns as the lily[1].

We predicted that readers' interpretation of the life and death of women could be polysemous or ambiguous in the last part, as she was dead as "herself" but alive as a lily.

## Participants

We collected data from 1,800 participants. Owing to the absence of similar studies, it was difficult to estimate the effect size. Therefore, we followed Wang et al. (2014), who employed QQ equality to test the quantum model for the order effect, and recruited approximately 100 participants in their lab experiments to determine the number of participants. As noted in the procedure, participants respond at the end of one of the paragraph 18. For each response to one paragraph end, 100 participants were randomly assigned. Only the participants who answered the Instructional Manipulation Check (IMC) correctly proceeded to the main task. The participants were paid 260 yen (approximately 1.8 dollars) only if they finished the main task.

## Procedure

Each participant was registered on CrowdWorks and participated in the experiment by accessing Qualtrics online through a web browser. They can access Qualtrics using only a personal computer and not a smartphone.

[1]In Japanese, lily is written as "百合." "百" means "100" and "合" means "meat."

After agreeing to participate in the study, each participant completed the IMC, confirming that they read the task instructions appropriately. Only participants who passed the IMC proceeded to the main task and completed the experiment.

In the main task, participants read the "Dai-ichiya" (please also see Figure 1). Each paragraph of the story was displayed on a single page. Participants read one paragraph and then clicked the button to move to the next page, and the next paragraph was presented. At the end of one of the 18 paragraphs, two questions were presented individually per page. The one is "Do you think the woman is alive?" and the other is "Do you think the woman is dead?" Participants clicked the "Yes" or "No" button to respond to these questions. After clicking the button, the other question was represented on the next page, and again, they answered by clicking the "Yes" or "No" button. The order of the questions was randomized. If the cognitive states are quantum, an observation can change them. This observation effect causes the order effect that this study focuses on (Wang et al., 2014). Also due to this observation effect, there is a possibility that the interpretation state of participants who have responded once may have changed. Therefore, participants can respond only at one paragraph end.

After answering the questions, participants read the remainder of the story. At the end of the story, all participants, except those who were asked the first question at the end of paragraph 18 (the end of the story), answered the same two questions. The order of the questions was randomized. Note that the answers to these questions at the end of the story are used for another study. We have not addressed these aspects in this current study.

After answering the questions at the end of the story, they completed a comprehension test. We asked the participants three questions to verify whether they understood the woman returning as a flower[2]. We then asked whether the participants had read the story before the experiment and if they knew the title of the story. We also asked participants about their reading experiences and comments on the experiment.

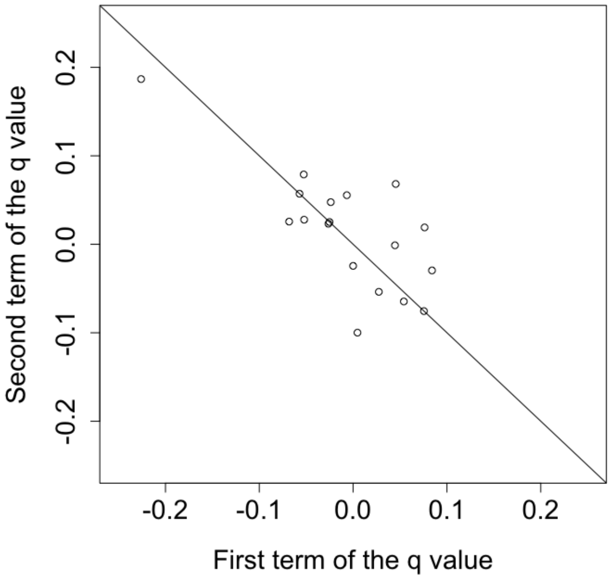



Figure 3: Scatter plot of the q value terms.

## Result

We excluded data from participants who answered Questions 1 and 2 incorrectly during the comprehension test. As the third question of the comprehension test had a broad range of interpretations, we did not use it for data selection. Consequently, 1,524 valid responses were analyzed.

Figure 2a and 2b show the time series of the ratio of the answers. In both figures, the red line represents the alive-first condition, and the blue line represents the death-first condition. In Figure 2a, the line with a circle represents Yes to alive and No to death, and the line with a cross represents No to alive and Yes to death, respectively. In Figure 2b, the line with a circle represents Yes to both the alive and death questions, and the line with a cross represents no response to both the alive and death questions. Due to the large proportion of participants who provided different answers to the two questions, the graphs are separated for clarity and visibility. Note that the units of the vertical axis in the two graphs are different.

Considering that it is explicitly stated that the woman is dead at the end of paragraph 11 (red dashed line), the ratio

[2]We do not take the position that there is a superior or correct interpretation of the reader in reading for pleasure. In this study, we conducted this comprehension test to examine the "indeterminate interpretation state" in readers who took the interpretation "the woman died but came back as a flower."

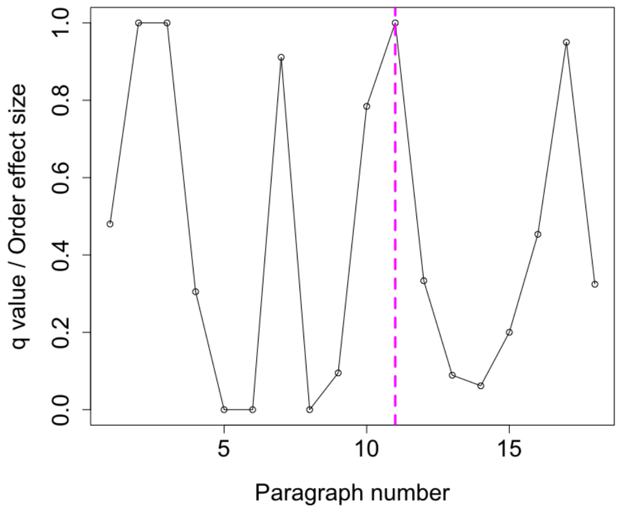



Figure 4: Time series of the normalized $q$ value. The red dashed line represents the end of Paragraph 11.

of answers changed drastically at this point. In addition to this change, the most significant trend in the results is shown at the end of paragraph 9 of Figure 2a. At this point, only under the alive-first condition did the ratio of answering Yes to alive and No to death decrease, while that of replying No to alive and Yes to death increased. This leads to the order effect becoming larger at this point than in the other paragraphs.

To verify the QQ equality, Following Wang et al. (2014), first, we compared $|q_{yy}+q_{nn}|$ and $|q_{yn}+q_{ny}|$ (we refer to these terms as "the size of the order effect" below) and selected the two terms included in the lager of the two for analysis.

The scatter plot of the $q$ value terms, which correspond to each size of the order effect, is shown in Figure 3. If $q$ is equal to zero, as predicted by QQ equality, the plots fall along a line with an intercept of zero and a slope of -1 (the line in Figure 3). The data appear to follow the predicted line, similar to the results in Wang et al. (2014). Owing to the emphasis on the time series estimation in this study, the sample size at each point in time was not sufficiently large to statistically test the predictions of QQ equality.

Figure 4 presents the time series of the normalized $q$ value. As the $q$ value is bounded by the size of the order effect, following Wang et al. (2014), we normalized the $q$ value by the size of the order effect and plotted it as a time series. The closer the normalized $q$ value is to zero, the more it tends to align with the prediction of QQ equality. This suggests a quantum nature that follows a model based on quantum probability theory. As the normalized $q$ value approaches 1 and the size of order effect approaches zero, it can be interpreted as classical, adhering to a model based on the classical probability theory. We can observe a trend in which the normalized $q$ value is close to 0 from Paragraphs 5 to 9 and from Paragraphs 13 to 14.

## Discussion

We observed the order effect, which can be related to the quantum effect, at the end of paragraph 9. The scatter plot of the terms of the $q$ value and the time series of the normalized $q$ values support the prediction of the QQ equality, particularly from paragraphs 5 to 9 and paragraphs 13 to 14. In summary, these results suggest that a reader's interpretation state at some point can be regarded as a superposition state.

Regarding the time series, this trend can be interpreted as a decrease in the normalized $q$ value, which indicates an increase in quantum indeterminacy, when a woman's life or death becomes uncertain. Paragraphs 5-9 suggest the woman will die soon, but the reader cannot predict the point of her death. In paragraphs 13 to 14, the readers expect her to return, but they cannot predict the point of coming. These contexts make the interpretations of life and death polysemic.

In contrast, there is a trend in which the normalized $q$ value is close to 1 and the size of the order effect is not so large, indicating that the state can be explained within the framework of classical probability theory, at the beginning of the story, end of paragraph 11, and end of the story. At the end of paragraph 8, the normalized $q$ value increases. A common feature of the story is that there is little polysemy regarding the woman's life and death. At the beginning of the story, readers construct their interpretation, which is not polysemous but a confused state (Gernsbacher et al., 1990). At the end of paragraph 8, the man asks the woman, and the reader can predict that the woman will answer in the next paragraph (therefore, the woman should be alive). Paragraph 11 explicitly states that the woman died.

In summary, the reader's interpretation state becomes quantum, which can be interpreted as an indeterminate state based on the multiplicity of the woman's life and death. We also pointed out that the normalized $q$ value can distinguish two types of indeterminacy: a polysemic interpretation state in which multiple interpretations coexist with indeterminacy and a confused interpretation state where no appropriate interpretation has been constructed.

These findings enhance our understanding of polysemous interpretations. A previous study hypothesized that readers construct the most plausible interpretation based on context and their knowledge (Gernsbacher et al., 1990; Kintsch, 1988). Our findings suggest that readers can hold multiple interpretations and remain indeterminate without deciding the correct interpretation. This indeterminate state can be represented as a superposition state, which is also a comprehension state, but with indeterminacy and emergent interpretation.

Previous studies considered that readers' text comprehension can be represented by a set of propositions (Kintsch, 1988). This implicitly assumes that readers' comprehension can be represented by natural language. However, the results of this study suggest that the reader's interpretation state can be superposed with interference terms, which cannot be reduced to the sum of propositions expressible in natural language. This provides a new perspective for comprehension studies.

Integrating the hypotheses of past studies and the findings of this study, we suggest that readers construct one comprehension state, but this state can be a superposition of multiple interpretations, some of which cannot be represented using natural language. This suggestion corresponds to past considerations in the literature and aesthetics (Iser, 1976; Eco, 1989). Fuyama (2023) also suggested that the comprehension of several metaphorical sentences can be regarded as the superposition state. On the contrary, Qian and Dell (2024) found no evidence of a quantum nature in readers' comprehension states concerning late-closure ambiguity. These findings, including the results of this study, suggest that there are two types of text comprehensions with ambiguity and polysemy: one with a quantum nature and another without. Further studies should be conducted to characterize the difference between these two types of text comprehensions.

We should also note certain exceptions. Based on this line of thinking, it is difficult to interpret why the normalized $q$ value increases around the end of the story because we hypothesized that the woman's life and death are polysemous at this point. Furthermore, at the end of paragraph 5, the woman's utterance in the following paragraph is suggested, but the normalized $q$ value is small. More experiments are required to characterize the normalized $q$ values when reading stories.

We discuss future research possibilities concerning the experimental setup that makes it challenging to answer both questions "Do you think the woman is alive?" and "Do you think the woman is dead?" with a simple "yes" or "no", and the subsequent modeling of the results. The authors assumed the potential transformation of the semantic space in which, as the narrative progresses, the woman transitions from being deceased as a person to being revived as a flower, thus altering the dichotomy of life and death. However, the number of respondents who answered "yes" or "no" to both questions was low. Consequently, there remains the possibility that life and death retained their antonymous nature within the semantic space. In such a case, where life and death remain orthogonal in the Hilbert space, explanations based on interference terms for order effects, as proposed by Wang et al. (2014), may be unsuitable. In this case, a model using the instruments proposed by Ozawa and Khrennikov (2021) might prove more effective for explaining the order effect and predicting QQ equality. As one issue of the experimental setup, the questions might have been too direct, affording no room for the reader to have multiple interpretations of the narrative; this, subsequently, might have hindered the accurate observation of ambiguous comprehension. To alleviate this issue, it would be beneficial to make the questions more nuanced. Improving the experimental design and/or modeling to address these challenges is important for future work.

In quantum cognition, this study contributes to the literature by presenting the results for relatively long-duration transitions in quantum cognitive states. Previous quantum cognition studies have dealt with relatively short-term temporal changes, such as cognitive state changes during a minute-long decision-making process (Kvam, Busemeyer, & Pleskac, 2021). In addition, this study addresses the quantum nature of cognitive states under the continuous input of nonstationary external information in the form of literary texts. Owing to the complexity of the conditions involved in this estimation, while previous studies estimated the cognitive states themselves, our study estimated the temporal changes in the quantum nature of cognitive states as $q$ values. Despite this limitation, the proposed method for estimating changes in the quantum nature of the cognitive state during relatively long and natural conditions, such as short story comprehension (averaging approximately 10 min), may open new avenues for future research on quantum cognition.

One further limitation of this study is that we did not consider participants' reading traits and experiences. If more cognitive resources and experience are required to construct a superposition state, whether a reader's interpretation state becomes superposed depends on their reading experience or working memory capacity. However, this study used order effects in all participants' data to test whether they were in a superposition state, assuming that all participants were in similar states on average. In a future study, we plan to obtain data regarding individual differences in reading experience and traits together and explore which readers are more likely to adopt the superposition state.

Concerning this point, it is also possible to examine whether indeterminacy promotes readers' immersion (Iser, 1976) using measures such as the transportation scale (Green & Brock, 2000). It is expected that investigating the relationship between the emotional or experiential aspect and the indeterminate state will contribute to clarifying the function and characteristics of the indeterminate interpretation state in understanding literature and art.

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