Reappraising the relationships between physics students' mental models and predictions: An example of heat convection

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Although prediction is claimed to be a prime function of mental models, to what extent students can run their mental models to make predictions of physical phenomena remains uncertain. The purpose of this study, therefore, was first to investigate 30 physics students' mental models of heat convection, and then to examine the relationship between their mental models and predictions of convection-related phenomena. A series of semistructured interviews was conducted to probe the participants' mental models and predictions of heat convection, and the constant comparative method was adopted for data analysis. The results reveal that the participants held a variety of mental models of heat convection, and nearly half held flawed mental models rather than a scientifically compatible one. In addition, while many participants attempted to run their mental models to make a prediction at the beginning stage of solving an interview problem, the relationship between the models and predictions became increasingly complex as the problem solving process continued. The relationships between mental models and predictions, however, could be better understood by considering the completeness of a mental model, the scale of analyzing mental models, and the retrieval of different formats of mental representations.

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I. INTRODUCTION

Helping students construct scientifically compatible mental models is a central goal of physics education [1–5]. To achieve this goal, it is of priority to investigate what mental models students have in order to “teach them accordingly” [6] as suggested by the constructivist framework [7,8]. While the characteristic function of a mental model is claimed to be its predictive and explanative power [9–11], whether students directly use their mental models to make predictions remains uncertain [12]. The present study, therefore, aims not only to investigate students' mental models, but also to explore the relationships between their mental models and predictions by using heat convection as an example of the physical phenomenon under study.

Mental models refer to people's internal representations which share analogous structures with the external physical phenomena or systems [10,11,13]. The distinctive characteristic of a mental model is its analogous relation to the target system to be represented. In other words, there is a correspondence between a mental model and the target system in terms of both the components and the structural relationships among these components within the system. Based on this analogous structure, “running” a mental model refers to mentally simulating the changing states of its components within the constraints of their mutual

relationships [1,14]. Moreover, the result achieved by running a mental model can be “read out” as the prediction for the final states of a given system. It is from this perspective that mental models are capable of fulfilling a prediction.

The relationships between mental models and predictions, nonetheless, may not be as straightforward as previously described. Their complicated relationships can be attributed to the uncertainty of both the format and the underlying mechanism of mental models. For example, regarding the format issue, no consensus has been reached regarding whether mental models consist of only imagery representations or include propositional ones [15,16]. Moreover, some empirical studies have shown that predictions might not be made exclusively from the manipulation of mental models but might rely on proposition-based reasoning instead [12,17]. In order to fully understand the nature and function of mental models, this study suggests that science educators need to carefully examine the relationship between mental models and predictions.

Although how people construct mental models remains an unresolved issue [18–20], there is a general agreement that mental model construction is a developmental process. In essence, the development of a mental model undergoes a series of conceptual changes [9,19–21]. When receiving unexpected information from the social or natural environment, people may change their corresponding beliefs and reorganize their belief or conceptual systems accordingly. People's mental models, in an optimist view, change from naive ones toward scientifically compatible ones. The developmental nature of mental models highlights the importance of investigating students' existing mental models as knowing the variation in students' mental models can

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inform teachers how to help students not only avoid alternative pathways of development, but also move toward scientifically compatible ones.

In recognition of the importance of investigating students' mental models, this study used heat convection as a context to investigate students' mental models and predictions for the following two reasons. First, although science educators have reached an impressive accomplishment in understanding students' ideas about heat and temperature [22–24], few studies have been conducted to specifically explore students' mental models of heat convection. Given that we all receive constant exposure to convection-related phenomena in our everyday physical surroundings, it is of value to investigate students' mental models of heat convection and how they use these mental models to make predictions for related phenomena. Second, because heat convection is a dynamic process rather than a static state, traditional ways to elicit students' alternative conceptions may be unable to fully capture its dynamic and systemic nature. As mentioned previously, mental models can be dynamically “run” to simulate external phenomena, and are thus suggested to provide a better approach to representing students' understanding of the dynamic process of heat convection.

II. RESEARCH PURPOSE

The purpose of this study was to investigate college physics students' mental models of heat convection and to explore the relationships between their mental models and predictions. Moreover, to explore this relationship in greater depth, this study also elicited the students' reasons behind their predictions. Accordingly, the correlations between their predictions and explanations and between their mental models and explanations could be further examined. Hopefully, the findings of this study can offer suggestions for helping students not only construct proper mental models of heat convection, but also apply these mental models in a more productive way.

III. METHODS

This study used the qualitative research method to investigate the participants' predictions and mental models of heat convection. A series of semistructured, generative interview questions [19,20] was designed to probe the participants' mental models by asking them to predict and explain convection-related phenomena. As suggested by many researchers [19,20,25,26], using this qualitative approach is a promising way to capture people's working mental models.

A. Participants

A cohort of 30 undergraduate physics majors (20 male and 10 female students) volunteered to participate in this study. This study recruited undergraduate physics students

as the participants because they were expected to be more capable of running their mental models [27] and to possess more diverse mental models than other students [17]. The participants were in their junior or senior year at college, and were between 21 and 23 years old. Before participating in this study, all of them had completed their required courses in the physics program, including thermal physics. The participants were therefore assumed to have constructed basic understanding of heat convection. In addition, all participants had practiced some thinking-aloud tasks before the interview and expressed their confidence in thinking and verbalizing their thoughts at the same time.

B. Materials and data collection

Three semistructured interview protocols were designed to elicit the participants' mental models of heat convection. The first interview protocol aimed to investigate their understanding of heat convection as well as some basic scientific concepts in thermal physics, such as heat and temperature. The interview questions in this protocol, for instance, included “Please describe your understanding of heat convection,” “please give some examples of phenomena related to heat convection,” “please describe the mechanisms underlying heat transfer,” and “please describe your understanding of heat.” In addition, for each question, some follow-up questions were posed to ask the participants to elaborate their thoughts, such as “would you explain why this happens?,” “can you give more examples?,” and “can you express your thoughts in another way?” The participants' responses to this set of questions were expected to provide a foundation as well as a reference frame to further interpret their mental models of convection.

In the second interview protocol, four interview-about-event questions [28] were designed to probe the participants' predictions and mental models of heat convection. As suggested by Vosniadou and Brewer [19,20], interview-about-event questions, like generative questions, provide a problem situation that requires participants to mobilize their mental models to solve the problem. Figure 1 is an example of an interview-about-event question used in this study (the other three interview questions are provided in the appendix). For each question, the participants were first asked to predict the final state of the problem situation through thinking aloud. Then, a series of follow-up questions was posed to investigate how the participants mentally simulated the process of heat convection to reach their predictions. For instance, the follow-up questions included “Can you describe the dynamic process of heat convection in more detail?,” “How do you image the process of heat convection in this situation?,” “Can you explain why convection occurs in this way?,” “How does convection affect the temperature of the liquid?,” etc. In addition to verbal responses, the participants were required to write down their predictions and explanations for every problem,

Interview question: As shown in the following picture, two identical tubes are filled with water of the same volume and from the same source. If we start to use two identical alcohol lamps to heat the two tubes at two different positions at the same time, one is heated at the bottom (Tube I) and the other is heated at the mid part (Tube II), the water in which tube will boil first? Why?

FIG. 1. An example of the interview questions in the second protocol.

as well as draw their imagery visualizations of the ongoing process of heat convection.

In the third interview protocol, several questions were posed to probe the participants' reflections on their previous responses. The interview questions, for instance, included "Do you want to change any of your answer to the previous question? Why?," "Did you learn anything new about heat convection during the interview?," "Do you feel confident about your answers to the questions?," etc. The participants' responses to these questions were used to make sure that the participants had provided affirmative answers and satisfactory responses for future analyses.

To summarize, these three sets of interviews were conducted to probe not only the participants' understanding but also their mental models of heat convection. The participants spent an average of two hours completing the three sets of interviews. In addition, among these three sets of interviews, the interview-about-event questions required the participants to make predictions and provide explanations about a specific problem situation, which offered an informative way to capture their mental model simulations. Moreover, throughout the interview process, the participants were encouraged to express their ideas in any feasible ways, such as verbalization, drawing, and writing. These different data formats served as multiple windows to disclose the participants' mental models of heat convection.

C. Data analysis

The constant comparison method [29] was adopted to analyze the data collected as three major types: verbalization, drawing, and writing. Because the purpose of this study is to investigate the participants' mental models and predictions of heat convection, the focus of data analysis

was placed on their responses to the second interview protocol set. As mentioned previously, the participants' responses to the first and third interview protocol sets served mainly as a reference frame to validate the interpretation of their mental models.

The data analysis focused on two major themes: the participants' mental models and predictions. Regarding their mental models, three rounds of data analysis were conducted to construct each participant's mental model of heat convection. The first round focused on the individual level of the models. Each participant's drawings of heat convection were first analyzed to check how they conceptualized the movement of convection currents. Then, the focus was placed on the changes in the spatial arrangements and temperatures of different parts of the liquid as a result of convection currents. In turn, cross comparisons among each participant's verbal utterances, drawings, and writings were performed to validate their mental models across the four interview scenarios. The second round analyses aimed to identify patterns among the 30 individual mental models obtained in the first round of analysis. In this round of analyses, the constant comparison method [29] was used to categorize the 30 mental models by checking their similarities and differences. As temporary categories were formed, a coding scheme was established by providing each category with both a label to characterize its distinct features and a coding instruction to guide further analyses. The purpose of the third round of analysis was to examine the reliability of the temporary coding results. Another science educator was invited to use the coding scheme to recode each participant's mental models. At this stage, the second coder might suggest revising the coding scheme by adding a new category or deleting an existing category. The intercoder reliability was calculated

as a Kappa coefficient, which was 0.92 ($p < 0.05$), indicating excellent agreement between the two coders. In addition, any discrepant coding result was discussed by the two coders until a consensus was reached.

The analyses of the participants' predictions and explanations were also conducted through the constant comparison method [29]. The participants' answers to the final state of each problem were first checked and patterns of their predictions were created accordingly. Similarly, the explanations accompanying the participants' predictions were thoroughly examined and then grouped into proper categories. Again, another science educator was asked to recode the participants' predictions and explanations, and the intercoder reliability was examined by calculating the Kappa coefficient, which was 0.86 ($p < 0.05$), once again showing excellent agreement between the two coders.

IV. RESULTS

This section, based on the results of the four interview-about-event questions, first presents the patterns of the participants' mental models of heat convection and provides a framework to discriminate among the patterns. It then, by using one of the interview-about-event questions as an example, demonstrates the relationship between the participants' mental models and predictions, as well as the reasons behind their predictions.

A. Mental models of heat convection

As shown in Table I and Fig. 2, seven patterns of mental models of heat convection were constructed based on the participants' responses to the interview questions. Table I also illustrates the features and frequencies of each mental model. It is worth noting that, although the list in Table I starts with a naive model and ends up with a scientifically compatible one, the order of these seven mental models does not imply a developing trend of scientific sophistication.

1. Model 1: Diffusion-based convection

The characteristic feature of model 1 is its diffusion-based mechanism of heat transmission. For example, when being asked to describe the process of heat convection, student S2 replied:

S2: *The water here (pointing at the lamp) is warmer, and it will transmit heat to its neighbors and make this water (pointing at the water in the upper area) warmer. This process is just like the heat moving up.*

R: *When thinking about this question, did you use any visualized imagination?*

S2: *Yes. I visualized how heat flows. It is just like conduction or diffusion; heat flows from here (pointing at the lamp) straight to the cold (pointing at the surface).*

As illustrated in the previous excerpt from the interview, S2 used the process of diffusion to simulate the way of heat transmission in a liquid. Heat, acting like a substance, spreads from the heat source (or the warmer part) and gradually moves toward the cooler part; no current or flow is needed to carry out heat transmission in this model. As heat diffusion begins, a gradual increase of temperature starts from the warmer part toward the cooler part in a stepwise fashion within the liquid. In essence, this model focuses only on how "heat" itself spreads outward but omits the liquid as the carrier of the heat transmission.

2. Model 2: Gradual-expanding convection

The feature of model 2 is its expanding scope of convective currents. In this model, convection starts with a small circular region and this region keeps expanding as convection proceeds. Within the convection region, the heated, warmer current moves up and the cooler current drops down; the warmer and the cooler current consecutively form a cycling current. The boundary of the expanding convection region is drawn by the top edge where the warmer current can maximally achieve in each cycle. The temperature within a convection region is entirely the same, and this temperature is higher than that of the outside region. As the convection region expands, the rising warmer current penetrates into its upper contiguous part and makes this part warmer. The temperature outside the convection region remains unchanged until the warmer convective current arrives. The following quotation illustrates how the participant (S4) described the process of heat convection in this model:

S4: *The process of heat convection is gradual. That is, because this part (pointing at the water just above the lamp) is heated first, a tiny convection current first occurs at the beginning stage. Then, as the water within this convection current reaches thermal equilibrium, the convection expands, and goes on to move up. The convection just continues in this way, gradually moving up, moving up ..., and finally, all of the water will become involved in the convection.*

3. Model 3: Evenly distributed convection

The central feature of model 3 is its equal temperature throughout a liquid at any moment of heat transmission, as exemplified by the following excerpt from the interview with S14:

R: *Would you please tell me what you were thinking about this question?*

S14: *I was thinking about how the convection current is running ... OK! When the water is heated, here (pointing at the water above the lamp) it becomes warmer, and its temperature is higher [than that at*

TABLE I. Patterns of the participants' mental models of heat convection. Note that the "heat source" in this table can be generalized to any warmer substance within a liquid. In addition, this heat source need not be located below the liquid; "top" and "bottom" are just used to refer to the relative positions of a convection current and a heat source.

Categories	Description	Frequency
Model 1 Diffusion-based convection	The underlying mechanism of heat transmission is similar to diffusion—heat spreads from the warmer part to the cooler part without the aid of current movements. The temperature is warmer at the part closest to the heat source and gradually decreases toward the other part.	1 (3.3%)
Model 2 Gradual-expanding convection	At the beginning, only a small cycling current is formed at the bottom of a liquid, and this cycling current keeps growing and gradually expanding toward the surface of the water. The temperature within the cycling region is the same, while the temperature outside the cycling region remains unchanged.	5 (16.7%)
Model 3 Evenly distributed convection	Cycling currents start to flow throughout a liquid immediately after heating starts at the bottom of the liquid. The currents receive heat from the heat sources and then immediately and evenly distribute the received heat all over the liquid. The temperature, therefore, is the same throughout the liquid.	1 (3.3%)
Model 4 Warmness-topped convection (I)	Cycling currents start to flow as soon as heating starts at the bottom of a liquid. The cycling current receives heat from the bottom of the liquid, becomes warmer, and then immediately rises up toward the top <i>without</i> releasing any amount of heat. After reaching the top, the current starts to sink and to release heat on its way down to the bottom. Because the current brings heat intact to the top, the top liquid has the highest temperature among other parts of the liquid.	1 (3.3%)
Model 5 Warmness-topped convection (II)	Cycling currents start to flow as soon as heating starts at the bottom of a liquid. The cycling current receives heat from the bottom of the liquid, becomes warmer, and then immediately rises up toward the top <i>without</i> releasing any amount of heat. After reaching the top, the current starts to sink and to release heat on its way down to the bottom. On the way heat is brought intact up to the top, heating continues at the bottom of the liquid. Accordingly, the bottom liquid has the highest temperature, while the top liquid has the second highest temperature in the liquid.	2 (6.7%)
Model 6 Rim-circulated convection	Cycling currents start to flow along the rim of the container as soon as heating starts at the bottom of a liquid; the middle part is not involved in the cycling current. The cycling current receives heat from the bottom of the liquid, becomes warmer, and rises up toward the top. After reaching the top, the current starts to sink down toward the bottom. In every cycle, the current neither penetrates nor releases heat into the middle part of the liquid; the current just flows around the rim of the container and keeps receiving heat from the heat source. As a result, among the different parts of the liquid, the bottom has the highest temperature, the top has the second highest temperature, but the central part's temperature remains unchanged.	3 (10%)
Model 7 Fluent-cycled convection	Cycling currents start to flow as soon as heating starts at the bottom of a liquid. The cycling current receives heat from the bottom of the liquid, becomes warmer, and then immediately rises up toward the top. On its way up, the current keeps releasing heat to its adjacent regions. After reaching the top, the current starts to sink down toward the bottom. On its way down, the current keeps absorbing heat from its adjacent regions. Accordingly, the bottom liquid has the highest temperature, and the temperature gradually decreases toward the top of the liquid.	17 (56.7%)

the top]. Then, convection occurs, and then the water in the tube starts to flow ...

R: *How about the temperatures of different parts of the water when convection occurs?*

S14: *The temperatures of different parts of the water will be the same because of convection.*

In this model, as a liquid starts to be heated at its bottom, a warmer current simultaneously rises up and moves toward the top of the liquid. As the warmer current reaches the top, it immediately sinks down and flows toward the bottom. As heating proceeds, the rising and sinking current

together form a cycling current and repeat continuously. This cycling current receives heat energy from the heat source at the bottom of the liquid, and then immediately and evenly distributes the received heat energy throughout the liquid. Because the heat energy is evenly distributed all over the liquid, the whole liquid shares the same temperature at any moment during the process of heat transmission.

4. Model 4: Warmness-topped convection (I)

The feature of model 4 is that the top part of a liquid has the highest temperature during heat transmission.

FIG. 2. Illustrations of the seven mental models.

The following quotations illustrate the feature of this model:

S23: ... *Let me think. Now the water here (pointing at the water above the lamp) is heated, and if the convection current reaches the top, the top will become the warmest, and here (pointing at the water just below the top) will be cooler [than the top], and here (pointing at the mid part of the water) will be even cooler.*

R: *Why is the top the warmest?*

S23: *Because the water with the largest volume will move up to the surface ... the largest volume [of water] has the smallest density.*

Similar to model 3, as soon as a liquid starts to be heated at its bottom, a cycling current is formed by a rising warmer current and a sinking cooler current. In contrast to model 3, after receiving heat energy from a heat source at the bottom, the warmer current keeps all the received energy intact on its way to the top and only starts to release its energy on its way down to the bottom. Right before the sinking current touches the bottom, it has lost most of the received energy. In consequence, as this current touches the bottom, it starts to receive heat from the heat source, becomes warmer, and begins to rise again; repeatedly, a new cycle begins. In every cycle, the top part of the liquid has the highest temperature because it contains all received heat that is brought intact by the rising current.

5. Model 5: Warmness-topped convection (II)

The feature of model 5 is its higher temperature at the top of a liquid during heat transmission, as exemplified by the following excerpt from the interview with S12:

S12: *Heating starts at the bottom part [of the water], so the [bottom] water becomes less dense first. Then, the current moves up to the surface [of the water], and the temperature of the surface becomes warmer, and then the cycling starts Because the heating starts from the bottom, the bottom part has the highest temperature. Then, the heat is transmitted to the top [of the water], and then down to the middle part [of the water]. As heating continues, the bottom part is still the warmest. And*

because the bottom part is the warmest, the heat is immediately delivered to the top again [by the convection current], and then the current sinks down. So, the top is warmer than the middle part of the water.

Similar to model 4, a cycling current forms as soon as heating starts at the bottom of a liquid. In addition, the rising current also keeps the received heat intact on its way up toward the top, and the sinking current also releases heat on its way down toward the bottom. In contrast to model 4, in this model, the highest temperature occurs at the bottom of the liquid, while the second highest temperature occurs at the top. This is because at intervals between the current starting to rise and reaching the top, the bottom part of the liquid keeps absorbing heat energy from the heat source and thus has accumulated more heat than the top part (which had no longer absorbed heat from the heat source since it started to rise). In brief, at any moment of any specific cycle of heat transmission, the bottom part of the liquid has always absorbed more heat than the top. The bottom, therefore, has the highest temperature, and the top has the second highest.

6. Model 6: Rim-circulated convection

While model 6 shares many common features with models 4 and 5, its distinct feature is the middle part's disengagement from the heat transmission in a liquid. Below is a sample excerpt from the interview with S6:

S6: ... *Now convection starts, and the lamp directly provides heat to the water here (pointing at the bottom part of the water). As the bottom water receives heat, the heat is carried by convection current and just moves up to the top. So, the top becomes warmer ... The warmest current (pointing at the bottom water) moves up, and as the current becomes cooler, it sinks down. Heat convection is a continuous process; as the warmer current moves up, the water nearby (pointing at the side rim of the container) just drops down to take up the space. So, the top water is warmer than the middle part; the temperature of the middle part stays the same.*

In this model, only the bottom and the top parts of the fluid are involved in the convection, while the middle part is isolated. Similar to models 4 and 5, as soon as a warmer current receives heat from the heat source at the bottom of the liquid, it keeps the received heat intact and immediately rushes up toward the top. In contrast to models 4 and 5, as the current sinks down toward the bottom, it does not release any heat but retains the received heat intact. In addition, the rising and sinking currents flow only around the rim of the container or boundary; the middle part is not involved in the convection, and its temperature remains unchanged during heat transmission. As in model 4, the bottom part has the highest temperature and the top part has the second highest temperature.

7. Model 7: *Fluent-cycled convection*

This model is the closest to a scientifically compatible one. The following excerpts exemplify how the participants accounted for the mechanism of this model:

S3: *If we have a tiny substance here (pointing at the surface of the water), if this is cooler than the water, it will keep on sinking down to the bottom. On its way down, its temperature will increase gradually; as it touches the bottom, its temperature will become the highest, so it will start to buoy up. And on its way up, it will eventually become cooler. Then, as it touches the surface and becomes much cooler, it will start to sink down.*

R: *Why does it start to buoy up when it becomes warmer?*

S3: *Because it will become less dense. When its density is lower, it will start to move up. And when it reaches the top, it becomes cooler than the water below, so it has a higher density and starts to sink down again.*

As illustrated in the previous excerpts, when the bottom part of a fluid is heated, it becomes the warmest and least dense, and then starts to rise. On its way up, the rising current keeps releasing heat to its adjacent regions (though only to a slight degree) and thus gradually becomes cooler. Therefore, as this current reaches the top, its temperature becomes the lowest among any other parts of the fluid, and it then starts to sink. On its way down, the sinking current keeps receiving heat from its adjacent regions and thus becomes warmer. As the current reaches the bottom, it directly receives heat from the heat source, becomes the warmest part of the liquid, and starts to rise again. The rising and sinking currents form a cycling current and continue repeatedly.

According to Table I, the frequencies of the seven mental models have an uneven distribution. For example, more than half of the participants (56.7%) held the scientifically accepted mental model (model 7). In contrast, three mental models (models 1, 3, and 5) were espoused by only one participant (3.3%). Moreover, models 2, 4, and 6 were

held by five, two, and three participants, respectively. In other words, while about half of the participants held a scientifically compatible mental model of heat convection, the other half held alternative models.

B. Framework to differentiate the seven models

According to the features of the seven mental models mentioned above, a framework was developed to differentiate them. As shown in Fig. 3, this framework involves six yes-no questions that address the essential differences to be identified among the seven models. The first question is about the mechanism underlying heat transmission in a liquid. If heat is not transmitted by cycling currents, then model 1 can be identified. More specifically, the mechanism of heat transmission in model 1 operates as diffusion, where heat gradually spreads from the heat source toward the cooler end.

As cycling currents are identified as the major mechanism of heat transmission, the second question focuses on the extent to which cycling currents can reach. If they do not extend from the bottom to the top of the fluid at the beginning stage of heat transmission, then model 2 can be distinguished. In model 2, convection starts only as small cycling currents near the heat source, and then gradually expands toward the top. The liquid outside the region of a cycling current is not involved in the convection, and its temperature remains unchanged.

As the cycling currents are confirmed to flow throughout a liquid, the following questions concern the temperature variation of the liquid. The third question, therefore, asks whether the entire liquid has the same temperature during heat transmission. If the entire liquid has an equal temperature, then model 3 can be identified. In model 3, the received heat energy is simultaneously and evenly distributed into all of the liquid by cycling currents, and thus the entire liquid shares the same temperature.

In contrast, if different parts of the fluid do not have the same temperature, then more possibilities need to be considered. Following the third question, the fourth question examines whether the top part of the liquid has the highest temperature. If the top is the warmest during the process of heat transmission, then model 4 can be identified. In model 4, the top is warmest because, as soon as the liquid is heated by the heat source at the bottom, a current rises and packs the absorbed heat toward the top. Accordingly, the top has the highest temperature.

However, if the top is not the warmest part of the fluid, then the next question can move on to consider the ranking of the temperature in different parts of the fluid. The fifth question, therefore, examines whether the top is warmer than the middle part of the fluid. If the top part is not warmer, then model 7 can be determined. In model 7, which is the closest to the scientifically accepted model, the bottom is the warmest because it directly receives heat energy from the heat source. As soon as the bottom part

FIG. 3. A framework to differentiate the seven models.

gets warmer, a current rises toward the top accompanied with releasing heat into its adjacent regions. As a result, when the rising current reaches the top, its temperature becomes the coolest among the other parts of the liquid.

Nonetheless, if the top part is indeed warmer than the middle part in a liquid, then how this temperature difference occurs deserves further exploration. The sixth question, therefore, considers whether the middle part is involved in heat transmission. If the middle part is involved, then model 5 can be identified. In model 5, a rising current does not release any heat until it starts to sink down. Moreover, the sinking current cools down because it keeps releasing heat to its adjacent regions. Accordingly, the top part is always warmer than the middle part. In

contrast, if the middle part is not involved in the heat transmission, then model 6 can be identified. In model 6, the rising warmer current can pack the absorbed heat energy intact, and directly reaches the top without releasing any heat. As a result, cycling currents seem to flow only along the rim of the container, and the middle part is isolated from the cycling.

C. Relationships between the participants' mental models and their predictions

In order to explore the relationship between the participants' mental models and predictions in depth, the following section will use the interview question illustrated in Fig. 1 as an example to present the results. However, it is

TABLE II. Cross comparison of the participants' mental models and predictions.

		Categories of prediction Which tube will come to a boil first?			Total
		Tube I	Tube II	The same time	
Mental model	Model 1	0	1	0	1
	Model 2	3	2	0	5
	Model 3	0	0	1	1
	Model 4	0	0	1	1
	Model 5	0	2	0	2
	Model 6	0	3	0	3
	Model 7	7	9	1	17
Total		10	17	3	30

worth noting that the seven patterns of mental models were constructed from the cross comparison of the participants' responses to all four interview questions. The following findings, therefore, reveal the relationship between the participants' generalized mental model and their predictions of a specific problem situation.

Table II shows the cross comparison between the participants' mental models and their predictions. It is worth noting that, before making their predictions, the interviewees had been explicitly informed that "boil" in this question referred to the state when the water turned into gas. According to Table II, among the ten participants who predicted that tube I will boil first, three held model 2 and seven held model 7. In addition, there were 17 participants who predicted that tube II will boil first, and they held a variety of mental models, including models 1, 2, 5, 6, and 7. Moreover, only three participants predicted that the two tubes will boil at the same time, and they held three different mental models, models 3, 4, and 7, respectively.

According to Table II, although there appears no overall salient correlation between the participants' mental models and predictions, some interesting relationships can be found if the models are used as the major reference to their predictions. For example, the participants who held models 1, 5, and 6 all made the correct prediction. In addition, the participants who held models 3 and 4 both predicted that the two tubes will boil at the same time. In brief, except for models 2 and 7, each of the other mental models correlates to only one category of prediction. In this respect, some of the participants' mental models might have a direct relationship with their predictions.

D. Reasons behind the participants' predictions

To better understand how the participants made predictions, their explanations for their predictions were further analyzed as shown in Table III. As summarized in Table III, the reasons for the prediction "Tube I will come to the boil first" can be grouped into three categories: A, B, and C. First, category A refers to the efficiency of

convection in the different tubes. The participants who gave this reason believed that, if a tube filled with water was heated at the bottom, instead of in the middle, convection would proceed at a greater extent within the water, and heat could be transferred into the water more efficiently. Accordingly, because the heat source is right under the bottom of tube I, the water in it will come to a boil more quickly than in tube II. Second, regarding category B, the participants emphasized that heat conduction acts as a barrier to heat convection in tube II. The participants who gave this reason believed that the lower half of the water can only receive heat through conduction, and thus the heat convection in tube II is blocked by the lower half of the water. Therefore, they predicted that tube I will come to a boil first. Third, with respect to category C, the participants believed that only when all the liquid reaches boiling point does boiling occur. They also believed that convection proceeds to a more thorough and efficient degree in tube I, and thus predicted that all the water in tube I will reach the boiling point and come to a boil first.

The reasons behind the prediction that "Tube II will come to the boil first" were coded into five categories: D, E, F, G, and H. First, in category D, the participants referred to the underlying mechanism of heat convection to make a prediction. They believed that, when heated, water becomes less dense and then moves upward. Accordingly, convection occurs only in the upper half of tube II, and this part will come to a boil first. Second, category E focuses on the volume of water involved in convection. The participants believed that, while all the water in tube I is involved in convection, only the upper half of the water in tube II is. That is, the volume of the upper half of the water in tube II is lower than that of all the water in tube I. Given that the two alcohol lamps provide the same amount of heat energy for the two tubes, the upper half of tube II will have the higher temperature and come to a boil first. Third, the reason coded as category F is a combination of categories D and E. In other words, the participants thought that tube II will come to a boil first not only because convection occurs only in the upper half of tube II, but also because the volume of the upper half of the water in tube II is lower than that of all the water in tube I. Fourth, category G refers to conduction as another factor above and beyond category F. In category G, the participants believed that the water in the bottom half of tube II transmits heat by heat conduction, which is not an efficient way of heat transmission within water. Therefore, in tube II, most of the heat energy provided by the alcohol lamp will be consumed by the upper half through convection, and thus the upper half of tube II will come to a boil first. Fifth, category H refers to a heuristic method as a rule of thumb. In this category, the participants used the distance between the heat source and the water surface to make the prediction. Because the distance is shorter in tube II than in tube I, tube II will come to a boil first.

TABLE III. The participants' explanations of their predictions.

		Categories of prediction			
		Tube I	Tube II	The same	Total
Reasons behind predictions					
A	In the case of tube I, because the alcohol lamp is right under the tube, convection occurs more thoroughly and efficiently.	4			4
B	In the case of tube II, because the water below the alcohol lamp transmits heat through conduction, convection occurs only above the lamp but not right throughout the tube. In contrast, because the alcohol lamp of tube I is right under the tube, convection occurs more thoroughly and efficiently than in tube II.	3			3
C	No boiling occurs until all the water reaches boiling point (100 °C). Regarding tube I, because the alcohol lamp is right under the water, convection proceeds more thoroughly and efficiently, and thus all the water will reach the boiling point more quickly than the water in tube II.	3			3
D	The warmer, less-dense convective currents stay in the upper half of tube II, and the lower half is not involved in the convection. Therefore, the upper water in tube II comes to a boil first.		3		3
E	Because the volume of the water above the alcohol lamp of tube II is less than the volume of all the water in tube I, the upper water in tube II comes to a boil more easily.		6		6
F	Because the warmer, less-dense water circulates only in the upper half of tube II, and because the volume of water above the alcohol lamp of tube II is less than the volume of all the water in tube I, the upper water in tube II comes to a boil first.		2		2
G	In tube II, the water below the alcohol lamp transmits heat energy by conduction, and convection occurs only above the lamp. Because the volume of the water above the alcohol lamp of tube II is less than the volume of all the water in tube I, the upper water in tube II comes to a boil first.		4		4
H	Because the alcohol lamp is closer to the surface of the water in tube II, the upper water in tube II comes to a boil first.		2		2
I	Because the amount of heat energy provided by the alcohol lamp and the volume of water in the two tubes are the same, both tubes come to a boil at the same time.			3	3
Total		10	17	3	30

Furthermore, there is only one common reason, category I, underlying the prediction that “the two tubes will boil at the same time.” Given that both tubes contain the same volume of water, when heated respectively by the same alcohol lamp, their temperatures will increase at the same rate. Therefore, the two tubes will come to a boil at the same time.

Table III also shows the frequency of each category. As can be seen, the frequencies of the nine categories range from 2 to 6, and there seems to be no salient feature of their distribution. However, some interesting facts can be found in Table III. For example, although seven participants (three from category B and four from category G) explicitly referred to conduction as the way of heat transmission in the bottom half of tube II, their different perceptions of how conduction worked in tube II led to different predictions. If the participants perceived conduction as a barrier to heat convection (category B), they would predict that tube I came to a boil first. In contrast, if the participants perceived conduction as a blockage that prevented heat energy from being lost into the bottom half, they would predict that tube II came to a boil first. In addition, some categories can be combined to form a larger one based on a

common factor. For instance, three categories, E, F, and G, use volume as a factor to determine the degree of temperature increase, and can be grouped into a larger category. Similarly, categories A, B, C, D, and G all refer to the scope of convection as a major indicator to determine which tube will come to a boil first, and thus can also be considered as a larger category.

E. Reexamining the relationship between mental models and predictions on a grand scale

The results shown in Tables II and III reveal that the participants' predictions might not directly rely on their detailed mental models of heat convection as shown in Table I, but might relate to how they conceived the appearance of conduction and convection in tube II from a broader perspective. Accordingly, this study moved further to analyze the participants' simulations of whether conduction and convection occurred in tube II as their grand-scale mental models of heat transmission. The grand-scale mental models of heat transmission refer to the participants' imagery visualizations about which way of heat transfer will occur in a problem situation (i.e., conduction, convection, or radiation), instead of detailed mental

TABLE IV. Cross comparison between the participants' predictions and the perceived mechanism of heat transmission.

	Prediction: Which tube will come to the boil first?			
	Tube I	Tube II	The same	Total
Mechanism of heat transfer in tube II				
Convection only	3	2	3	8
Convection and conduction	7	15	0	22
Total	10	17	3	30

simulations of the process or mechanism underlying any specific way of heat transfer. As shown in Table IV, the participants' simulations of heat transfer were coded into two broad categories. On the one hand, if the participants thought that only convection occurred throughout tube II, their responses were coded as *convection only*. On the other hand, if they believed that both convection and conduction were involved in heat transmission in tube II, and conceived that heat convection occurred only in the upper half and conduction controlled the lower half, their responses were coded as *convection and conduction*.

Figure 4 illustrates two examples of the participants' drawings of the heat transmission in tube II. In Fig. 4(a), the participant expressed that only convection occurs in tube II, and convection proceeds as two separate cycling currents which are above and below the heat source, respectively. In the upper half, the convection current first rises up to the top and then sinks down until it reaches the same level as the heat source; in the lower half, the convection current first drops to the very bottom of tube II and then rises up until it reaches the heat source. In Fig. 4(b), the participant sketched that convection occurs only in the upper half of tube II, and conduction is the dominant way of heat transfer in the lower half. As mentioned previously, these two different perceptions of the mechanism of heat transfer were coded as "convection only" and "convection and conduction," respectively.

Table IV shows the cross comparison between the participants' simulations of the heat transfer mechanism in tube II and their predictions of the original question. Among the ten participants who predicted that tube I will

come to a boil first, three thought only convection occurred, and the other seven believed that both convection and conduction were involved in heat transmission. In addition, among the 17 participants who predicted that tube II will come to a boil first, only two thought that convection was the sole way of heat transmission, while the remaining 15 believed that convection and conduction separately dominated different parts of the heat transmission. Moreover, all three participants who predicted that the two tubes will come to a boil at the same time all believed that only convection occurred in tube II. The result of a chi-square test [$\chi^2(2, N = 30) = 10.24$, $p = 0.006$] further suggests that the participants' predictions might significantly relate to their simulations of the heat transmission mechanism in tube II. For example, those who conceived that both conduction and convection occurred in tube II were more likely to make a correct prediction that tube II will come to a boil first.

V. DISCUSSION AND CONCLUSION

A. Investigation of the participants' mental models of heat convection

The results of this study reveal several merits of investigating students' mental models rather than their conceptions. First, given that heat convection is a dynamic process in nature, the investigation of students' mental models of heat convection can vividly capture their simulations of the corresponding dynamic process. Taking model 2 as an example, the participants perceived the process of heat convection as a cycling current that keeps growing and

(a) Only convection occurs.

(b) Both convection and conduction occur.

FIG. 4. Examples of the participants' drawings of the heat transmission in Tube II.

expanding toward the surface of the liquid. This dynamic process, however, could not have been fully investigated by traditional approaches to studying students' conceptions. Second, the investigation of students' mental models helps to further differentiate their conceptualizations of heat convection. For example, if the investigation focused only on a conception level, then "warmness rises and coldness sinks" could have been arrived at as a proper representation of students' understanding of heat convection. A model-based investigation, however, helps to distinguish various dynamic mechanisms underlying the conception of "warmness rises and coldness sinks," such as model 2 to model 7 identified in this study. Third, investigating students' mental models helps to identify their alternative conceptions of a convection system. For example, the participants who held model 3 might believe that (1) convection currents could immediately flow throughout a liquid right after heating starts, and (2) convection currents could evenly distribute absorbed heat energy within a liquid; as a result, (3) the entire liquid would have the same temperature at every moment of heat convection. That is, model 3 contains at least these three alternative conceptions which share a series of causal or spatial relationships among different components or portions within a convection system. In brief, beyond studies on students' conceptions, studies on students' mental models can provide in-depth information about their comprehension of the dynamic process of heat convection as a whole system, not just as a set of fragmented conceptions.

Moreover, according to the framework illustrated in Fig. 3, the major flaws in the participants' mental models can also be identified. The first flaw is about the carrier of heat transmission in a liquid. Regarding the first yes-no question in Fig. 3, the participant who held model 1 might conceptualize heat as a substance and thus mistook "heat" itself, instead of a current, as the agent of heat transmission. The second flaw is about the momentum of a rising convection current. With respect to the second yes-no question in Fig. 3, the participants who held model 2 might underestimate the momentum of a rising warmer current by ignoring the buoyant force given by the fluid beneath the rising current. The third flaw is about heat exchange occurring around convection currents. As addressed in the third, fourth, and fifth yes-no questions in Fig. 3, the participants who held model 3 to model 6 ignored the interaction between a rising or sinking current and its adjacent neighbors. That is, they failed to consider that a rising warmer current kept releasing heat to its adjacent neighbors on its way up to the cooler surface, and that a sinking cooler current absorbed heat from its adjacent neighbors on its way down to the warmer heat source. As a result, these participants tended to believe that heat energy was packed by a rising convection current and remained intact on its way up to the surface, and thus misjudged that the top part of the liquid would have a

higher, if not the highest, temperature. The fourth flaw is about the scope of heat convection. With respect to the sixth yes-no question in Fig. 3, the participants who held model 6 believed that convection only occurred within the beltlike region of a cycling current and never interacted with the central part of the liquid. In other words, they falsely conceptualize a convection phenomenon as one single convection current circulating in a two-dimensional plane, instead of a combination of multiple convection currents flowing around a three-dimensional space. Overall, a serious deficiency of the participants' flawed mental models could be the omission that a convection current is indeed a collective movement consisting of numerous molecular interactions resulting from heat exchange [17]. This omission could prevent the participants from carefully considering the actual carriers, the complicated associations between particle interactions and heat exchanges, and the exact scope of heat convection.

The mental models identified in this study provide some clues for uncovering how these mental models were constructed. For example, the participants' sketches of heat convection might be a crude copy of their textbook diagrams of heat convection. In general, most textbooks illustrate heat convection as a cycling current represented by one or two consecutive curved arrows [30,31]. The participants might just retain the typical feature of the textbook illustrations without carefully considering the detailed mechanism underlying the cycling current. As a result, although the participants' sketches shared the common typical feature of heat convection (as in model 2 to model 7 shown in Fig. 2), they constructed different explanations to account for the underlying mechanism.

Another clue for uncovering how mental models are constructed is the analogy used by the participants [16,21]. Based on the participants' verbal responses to the interview questions, all of them used the word "flow" to describe how convection currents moved. Presumably, the participants might rely on an ordinary but dominant "water flow" analogy to conceptualize heat convection. With the aid of the water flow analogy, the participants could be equipped with a sensory basis to "feel" and image how a cycling convection current moves. This analogy, however, might also impose some constraints on the participants' conceptualization of the process of heat convection if they had falsely conceived the mechanism underlying flowing water. For instance, if the students omitted the difference in height and never noticed that water usually moved "downhill" because of gravitational force, they might perceive that water could just flow "freely" and "naturally." This falsely perceived "flow" analogy might inhibit the participants from paying attention to the driven force of convection currents, i.e., a buoyant force exerting against the gravitational force. That is, if the participants believed a rising convection current moves upward just "naturally" as an "ordinary"

water flow does, they might be unaware of the need to figure out the mechanism underlying the driving force of the rising current. Moreover, this flow analogy might prevent the participants from adopting the microscopic view of heat convection. If the participants perceived a water flow as a holistic substance, they might conceptualize convection currents only from a macroscopic view, instead of as a series of molecular interactions. In this case, they would encounter difficulty in explaining how to differentiate heat conduction from convection, how rising convection currents release heat energy to their adjacent areas, and how convection currents turn into boiling vapor. As suggested by some researchers [17,32], the ontological beliefs embedded in the flow analogy might severely constrain how the participants conceptualize the underlying microscopic mechanism of heat convection.

B. Relationships between mental models and predictions

The results of this study demonstrate a complex relationship between the participants' mental models and predictions. This complexity can be addressed by two different levels of analysis. At a detailed level, if the participants' dynamic simulations of heat convection are categorized into seven mental models as shown in Table I, these seven models have no statistically significant correlation to their "final" predictions. Although some participants did attempt to run their mental models to make a prediction at the beginning, they did not persist in running them until reaching the final state of the problem situation. Instead, they switched to adopted related propositional statements to make a prediction, such as "convection transmits heat more efficiently than conduction," "a liquid comes to the boil only when all the liquid reaches boiling temperature," and "two liquids with the same volume will come to the boil at the same time if given the same amount of heat energy." The preference in adopting a propositional statement, rather than running a mental model, for making a prediction has also been found by some researchers [12,17]. The participants switching to adopt a propositional statement, nonetheless, might not result from their familiarity with the problem situation [12]. Rather, the switch might result from the need to consider the discontinuous situation between heat convection and vaporization in a liquid. That is, a mental model of heat convection could not simulate the process of phase transition from a liquid to a gaseous state. Therefore, to answer the question "which tube will come to the boil first," the participants need to recruit other cognitive resources in addition to their mental models of heat convection. Of course, the participants might have realized the most sophisticated way to answer the interview question at the very beginning, and just directly adopted related propositional statements to make their predictions. In either case, they did not run their mental models to make the final prediction, and,

consequently, their mental models had little correlation to their prediction.

On the other hand, from a grand-scale perspective, the participants' mental models of heat transmission did affect how they made the resultant prediction. As illustrated in Table IV, if the participants were aware that heat transmitted through conduction in the lower half but through convection in the upper half of tube II, they were more likely to make a correct prediction. In other words, by considering mental models from a grand scale but not a detailed, dynamic level (just focusing on the occurrence of convection currents but omitting how convection currents change the temperature condition in a liquid), students' simulations of whether heat convection and conduction occur in tube II can be treated as two separate grand-scale mental models of heat conduction and convection, respectively. Accordingly, if the participants successfully used these two grand-scale mental models to simulate the process of heat transmission in tube II, these two mental models could lead to a correct prediction. At this grand-scale level, it is evident that the participants' mental models, accompanied with relevant propositional statements, demonstrate significant relationships with their predictions.

In summary, to clarify the complex relationship between mental models and predictions, at least the following three aspects need to be addressed. The first refers to the level at which mental models are analyzed. While a detailed analysis can enrich the variation of students' mental models, this enriched variation also complicates the task of discovering the correlations between mental models and predictions. In contrast, while a grand-scale analysis provides only a rough sketch of students' mental models, this rough sketch conveys a grandstand view that supports the discovery of correlations between mental models and predictions. The second aspect concerns to what extent propositional statements are involved in making predictions. If propositions are directly retrieved from long-term memory for making predictions, then it will be extremely difficult to uncover the correlations between mental models and predictions. Last but not least, whether mental models and propositional statements are used in a "correct" way also determines how the models relate to predictions. In a broad sense, students' predictions would become unpredictable if a mental model is operated in an arbitrary way or a propositional statement is misconstrued as an alternative conception.

VI. IMPLICATIONS

The findings of this study can offer some suggestions for physics education practice and research. With respect to instructional practice, when teaching heat convection, for example, teachers should first provide guidance for students on how to observe and describe a complete convection cycle, and on how to perceive convection as a

collection of multiple convection currents. Then, teachers may introduce the detailed mechanism underlying the dynamic process of heat convection in terms of molecular interactions, particularly how convection currents rise against the gravitational force and how temperature changes as a result of convection currents in a liquid. Moreover, teachers need to provide students with firsthand experience of observing convection phenomena, instead of relying only on textbook illustrations to make the explanation; otherwise, students may conceptualize the textbook illustrations in multiple alternative ways. Regarding future research work, researchers are suggested to recruit a larger number of participants to examine whether the seven mental models found in this study are held by more than a few students. Also, researchers can further investigate whether students can adjust their mental models by observing the result of an actual experiment after making their predictions. Moreover, to establish a sounder foundation of mental model theories, future studies can focus on investigating how related analogies affect the construction of mental models, particularly the constraints imposed by a specific analogy. In addition, the complex relationships among mental models, predictions, and explanations deserve further exploration. This issue can be addressed from the nature of mental models, such as whether they contain only imagery representations or also include propositional ones. Furthermore, exploring how these different sorts of mental representations mutually interact during the process of running mental models may also help to resolve the complex relationships among mental models, predictions, and explanations.

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FIG. 5. Three interview questions.

APPENDIX: THE OTHER THREE INTERVIEW SCENARIOS

- (1) As shown in Fig. 5(a), if we drop an ice cube (100 g, -20°C , and $0.7 \text{ cal/g} \cdot ^{\circ}\text{C}$) into a beaker filled with water (300 g, 35°C , and $1 \text{ cal/g} \cdot ^{\circ}\text{C}$), after a long time, what may happen to the ice cube and the water? Why? Please draw down your thinking.
- (2) As shown in Fig. 5(b), if we drop an iron cube (100 g, 80°C , and $0.11 \text{ cal/g} \cdot ^{\circ}\text{C}$) into a beaker filled with water (300 g, 35°C , and $1 \text{ cal/g} \cdot ^{\circ}\text{C}$), after a long time, what may happen to the iron cube and the water? Why? Please draw down your thinking.
- (3) As shown in Fig. 5(c), if we drop a wood cube (100 g, 80°C , and $0.37 \text{ cal/g} \cdot ^{\circ}\text{C}$) into a beaker filled with water (300 g, 35°C , and $1 \text{ cal/g} \cdot ^{\circ}\text{C}$), after a long time, what may happen to the wood cube and the water? Why? Please draw down your thinking.

Note that all three interview questions included a series of follow-up questions beginning with “How” and “Why” to probe the participants’ in-depth understanding of heat convection.

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