Chapter 12
Examining the Relationships Among Intuition, Reasoning, and Conceptual Understanding in Physics

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Abstract It is a common expectation that, after instruction, students will consciously and systematically construct chains of reasoning that start from established scientific principles and lead to well-justified predictions. When student performance on course exams does not reveal such patterns, it is often assumed that students either do not possess a suitable understanding of the relevant physics or are unable to construct such inferential reasoning chains due to deficiencies in reasoning abilities. Psychological research on thinking and reasoning, however, seems to suggest that, in many cases, thinking processes follow paths that are strikingly different from those outlined above. A set of theoretical ideas, referred to broadly as dual process theory, asserts that human cognition relies on two largely independent thinking systems. The first of these systems is fast and intuitive, while the second is slow, logically deliberate, and effortful. In an ongoing project focusing on student reasoning in physics, we have been developing and applying various methodologies that allow us to disentangle reasoning, intuition, and conceptual understanding in physics. We then use the dual process theory to account for the observed patterns in student responses. Data from introductory physics courses are presented and implications for instruction are discussed.

12.1 Introduction

It is a common expectation that, after instruction, students will consciously and systematically construct chains of reasoning that start from established scientific principles and lead to well-justified predictions. When student performance on course exams does not reveal such patterns, it is often assumed that students either do not possess a suitable understanding of the relevant physics or are unable to construct such inferential reasoning chains due to deficiencies in reasoning abilities. Psychological research on thinking and reasoning, however, seems to suggest that,

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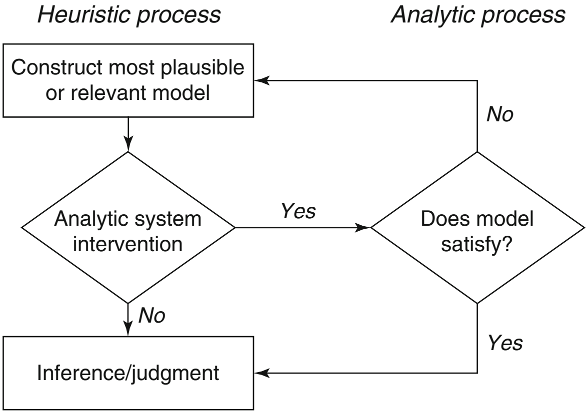

Fig. 12.1 Illustration of interactions between the heuristic and analytic processes (Evans 2006).

in many cases, thinking processes follow paths that are strikingly different from those outlined above. A set of theoretical ideas, referred to broadly as the dual process theory, asserts that human cognition relies on two largely independent thinking processes. The first of these processes is fast and intuitive (often referred to as the *heuristic* process), while the second is slow, logically deliberate, and effortful (often referred to as the *analytic* process). In an ongoing project focusing on student reasoning in physics, we have been developing and applying various methodologies that allow us to disentangle reasoning, intuition, and conceptual understanding. We then use the dual process theory to account for the observed patterns in student responses (Fig. 12.1).

The Dual Process Theory of reasoning suggests that two processes are involved in most cognitive tasks: heuristic and analytic. When a reasoner is presented with an unfamiliar situation, the quick and intuitive heuristic process immediately and subconsciously suggests a most plausible and relevant mental model for this situation. This "first available mental model" is based on the person's prior knowledge, experiences, and contextual cues. In everyday life, first available mental models are often described as "gut feelings" or "first impressions." In this study, we use the term intuition to refer to student ideas consistent with first available mental models suggested by the quick, subconscious, and automatic heuristic process. However, it is important to note that, in the context of physics instruction, first available mental models may not necessarily be based on students' everyday experiences. Such models may be based on formal ideas or reasoning approaches ubiquitous in physics, but not necessarily applicable to a situation at hand.

The role of the analytic process is to assess the validity of a first available mental model (See Fig. 12.1). However, if a reasoner feels confident in the answer suggested by the model, the analytic process is often bypassed. In such cases, this process yields a final, heuristic-based response. The engagement on the analytic process, however, does not always result in a rigorous and systematic assessment of the validity of a mental model due to reasoning biases. For example, if a reasoner believes that an answer suggested by a heuristic-based model is correct, the reasoner will search for evidence that supports what is already believed to be correct while neglecting to consider alternatives. This thinking pattern is often referred to as *confirmation bias*. While it has been argued that metacognition, or thinking about one's own thinking, is the key for engaging the analytic process more productively (Amsel et al. 2008), the mechanism for a productive evaluation of heuristic-based mental models is poorly understood. In this study we aim to probe conditions under which students are more likely to recognize inadequacies in their current mental models and to consider alternative solutions.

12.2 Methodology

In order to achieve our goal, it is imperative to design methodologies that would allow for the disentanglement of student conceptual understanding from their reasoning approaches. In the past several years, we have been designing sequences of screening and target questions in various physics contexts (Kryjevskaia and Stetzer 2014). Screening questions probe whether or not a student possesses the formal knowledge and skills necessary to analyze a specific situation correctly. A target question requires the application of the same knowledge and skills in a similar situation but may also elicit intuitive, rather than formal reasoning approaches. We then focus on analyzing responses to target questions of those students who answer the screening questions correctly, thereby demonstrating that they indeed possess the formal knowledge and skills necessary to successfully arrive at a correct answer to the target question. This approach allows us to insure that patterns of student responses on the target question are likely to be attributed to specific reasoning approaches rather than the lack of conceptual understanding.

Below we present a screening-target sequence of questions in the context of static friction administered in the first semester of introductory calculus-based physics course. We then discuss three different modes of metacognitive intervention along with the theoretical underpinnings that informed the design of these interventions. Results are interpreted through the lens of the dual process theory of reasoning.

12.3 Examples and Results

Original Screening-Target Sequence of Questions

On the screening question, students considered box A at rest on a rough surface. They were told that a horizontal 30 N force was applied to the box, as shown in Fig. 12.2a, and the box was observed to remain at rest. Students were asked to compare the magnitudes of the applied force and the force of friction. In order to answer the question correctly, students were expected to apply Newton's second law

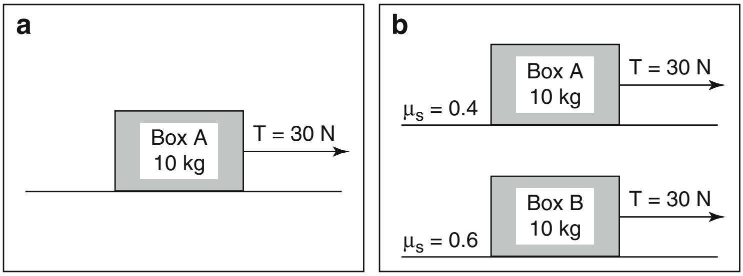

Fig. 12.2 Diagrams illustrating situations presented on (**a**) screening and (**b**) target questions

and to recognize that, since the box remains at rest, the net force on the box must be zero. As such, the magnitude of the force of friction must be equal to that of the applied force, $f_s = T = 30$ N.

The target question shown in Fig. 12.2b involved an analogous situation: two boxes of equal mass were placed on rough surfaces. Students were told that the coefficient of static friction μ_s between box A and a surface was 0.4, while the coefficient of static friction between box B and a different surface was 0.6. Identical 30 N horizontal forces were applied to each box; both boxes were observed to remain at rest. Students were asked to compare the magnitude of the force of friction acting on box A to that acting on box B. Both screening and target questions call for the application of the same reasoning approach: since both boxes remain at rest, the forces of friction must be equal to 30 N regardless of the roughness of the surfaces.

Most students were able to answer the screening question correctly, as shown in Table 12.1. However, ~23% of the students who applied the correct line of reasoning on the screening question failed to do so on the target question. Instead, these students argued that the force of friction on box A must be less than that on box B since $(\mu_s)_A < (\mu_s)_B$. Most of these students justified their answers by inappropriately applying various mathematical relationships between forces of friction and coefficients of friction such as $f_k = \mu_k N$ or $f_{s,\max} = \mu_s N$.

The application of the dual process theory suggests that the inclusion of the extraneous information on the screening question cued the mental model based on the relationships between the force of friction and the coefficient of friction. This resulted in the abandonment of the line of reasoning based on Newton's second law. The readily available and ubiquitous (in the context of introductory physics courses) mathematical relationships between these two quantities provided further confirmation for the validity of this mental model. As such, even though these students possessed the formal knowledge and skills necessary to answer the target question correctly, they did not feel compelled to examine the validity of their mental models either by checking for consistency between their answers to the screening and the target questions or by searching for alternative solutions.

The results from this screening-target sequence suggest that a fraction of incorrect student responses to the target question could be attributed to deficiencies in student reasoning approaches rather than the lack of knowledge and skills necessary to

Table 12.1 Results from student responses on sequences of screening-target questions

Original screening-target sequence ($N = 54$)		Metacognitive intervention 1 ($N = 53$)		Metacognitive intervention 2 ($N = 58$)		Metacognitive intervention 3 ($N = 224$)	
% of correct responses on the screening question							
81%		85%		57%		43%	
Distribution of responses on the target question of those students only who answered the screening question correctly							
Correct	Incorrect	Correct	Incorrect	Correct	Incorrect	Correct	Incorrect
77%	23%	76%	24%	76%	24%	73%	27%

answer the question correctly. As such, it is imperative to develop interventions that would engage students' analytic processes more productively and enable students to recognize shortcomings in their reasoning approaches. The three modes of metacognitive interventions described below were designed in order to probe impacts of various interventions on student reasoning patterns. All three interventions utilized the context of frictional force; the prevalence of incorrect student responses on the target question was used to gauge the effectiveness of these interventions.

Metacognitive Intervention 1: Opportunities for Considering Alternatives

In this sequence, a metacognitive question was designed to follow up the screening-target pair discussed above. The questions prompted students to (1) predict what answer other students would give if they applied intuitive thinking to the target question and (2) reflect on whether they themselves applied intuitive reasoning or formal knowledge. It is important to note that it was not the goal of this intervention to examine the students' abilities to distinguish between intuitive and formal thinking. Instead, we hoped that the metacognitive prompt would provide opportunities for the students to consider alternatives and to reflect on their own reasoning. This sequence was administered as part of a regular course exam. Students who responded to the metacognitive prompt received 1% of extra credit. The results from the metacognitive intervention 1, presented in Table 12.1, revealed no intervention-dependent difference in the student performance on the target question.

The results of metacognitive intervention 1 suggest that although this mode of intervention encouraged students to consider alternatives, it failed to create dissatisfaction with the students' current incorrect reasoning approaches. This apparent failure may be due to the state of *cognitive ease* that the screening-target sequence presents. Indeed, one of the functions of the heuristic process is to conduct a quick and subconscious assessment of a situation at hand. The heuristic process detects whether the situation presents any threat and whether or not some cognitive efforts must be redirected to the analytic process. If the heuristic process is not on alert (or is in the state of cognitive ease), the analytic process may not be engaged to its full potential. When the heuristic process detects "unease" (or is in the state of *cognitive strain*), the analytic process may be more fully engaged, such that a reasoner becomes more attentive and careful in his/her judgments (Kahneman 2011).

It may be argued that the screening question prompts students to apply the reasoning necessary to answer the target question correctly in a fairly simple context and, therefore, sets the students on the correct path in answering the target question. As such, the inclusion of the screening question makes it more likely for the students to answer the target question correctly. At the same time, it may be argued that the fairly straightforward solution to the screening question creates the state of cognitive ease. This, in turn, may impede student tendency to reflect on their thinking and to check for consistency between their reasoning on the screening and target questions. In other words, this state of cognitive ease may suppress student abilities to recognize reasoning pitfalls associated with the inappropriate application for the μ-based reasoning on the target question.

Metacognitive Interventions 2 and 3: Removing Cognitive Ease

Metacognitive interventions 2 and 3 were designed in order to probe whether or not the pattern of student responses on the target question could be altered by creating the cognitive strain on the screening question. Specifically, metacognitive intervention 2 contained a screening question that involved box A at rest on a rough surface with the coefficient of static friction $\mu = 0.5$. Students were told that a horizontal 30 N force was applied to the box, as shown in Fig. 12.3a, and the box remained at rest. The mass of box A was not specified. Students were asked to compare the magnitudes of the applied force and the force of friction. Students were prompted to state explicitly if not enough information was given to answer the question. The target question in this modified sequence was similar to that in the original version, except no masses for the two boxes were specified, as shown in Fig. 12.3b.

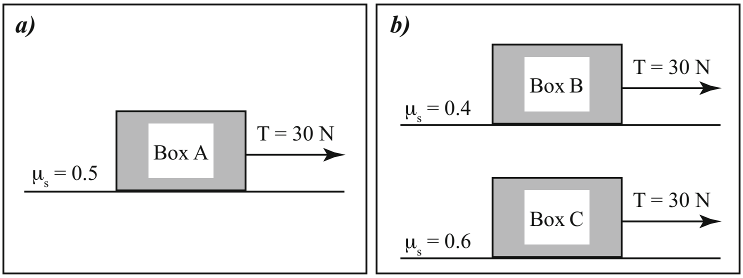

Fig. 12.3 Diagrams illustrating situations presented on (**a**) screening and (**b**) target questions of metacognitive intervention 2

We argued that this version of the screening question would create cognitive strain because the inclusion of the extraneous information (i.e., $\mu = 0.5$) would likely cue the reasoning approach based on the first available mental model "μ determines f," while the absence of information about the mass of the box would make it impossible to apply the mathematical relationship $f = \mu N$ inappropriately in order to justify the model and to determine the answer to the question. We hypothesized that the fraction of correct responses to this version of the screening question would decrease significantly, while the percentage of responses with inconsistent lines of reasoning on the screening and target questions would decrease. The latter hypothesis stemmed from the notion that those students, who correctly answer the screening question by rejecting the relevance of μ to the static situations, would not be likely to apply this rejected line of reasoning on the target question. Results presented in Table 12.1 suggest that our hypothesis was supported only partially. Indeed, while the percentage of correct responses on the screening question decreased, the pattern of inconsistent responses was not altered. On the target questions, ~20% of the students who answered the screening question correctly argued that "the higher coefficient of friction will lead to a great frictional force."

Metacognitive intervention 3 included a new version of the screening question designed to create cognitive strain by widening the space of possibilities through foregrounding the distinction between the cases of static and kinetic friction. Specifically, students considered a box at rest on a rough surface, which is observed to remain at rest after a hand exerted a horizontal force on the box, as shown in Fig. 12.4. Students were asked to identify which of the following piece or pieces of information are required in order to determine the magnitude of the force of static friction acting on the box: (a) the magnitude of the force exerted on the box by the hand, (b) the mass of the box, and (c) the coefficient of static friction between the box and the surface. Students were prompted to choose all that apply. The target question in this metacognitive intervention was identical to that in the original sequence. Much like on metacognitive intervention 2, we hypothesized that those students who correctly answer the screening question by rejecting the relevance of μ and the mass m to the static situations would not likely to apply this rejected line of reasoning on the target question. This version of the intervention, however, makes the rejection of the relevance of μ and m more explicit. Results presented in Table 12.1 suggest that all three modes of metacognitive intervention were unsuccessful in altering patterns of inconsistent student responses on the target question.

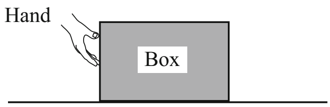

Fig. 12.4 A diagram illustrating a situation presented on a screening question of metacognitive intervention 3

12.4 Conclusions

The findings from our study serve to highlight the persistence and resilience of the kind of incorrect, intuitively appealing reasoning approaches often employed by introductory physics students. These observed intuitive approaches may not necessarily be based on everyday ideas related to a situation at hand (e.g., frictional force). In most cases even those students who demonstrated that they possessed the formal knowledge and skills necessary to answer the target question correctly did not feel compelled to examine the validity of their reasoning either by checking for consistency between their answers to the screening and the target questions or by searching for alternative solutions. Our results suggest that many students found confirmation of their intuitive ideas in misinterpreted formal mathematical relationships. As such, these students were particularly unlikely to question their first-impression answers.

We have presented data from three different metacognitive interventions designed on the basis of theoretical ideas rooted in the psychological research on reasoning and decision making and aimed at engaging students' analytic processes more productively. Despite these efforts, we have observed similar reasoning patterns on the target question in all three cases. This suggests that perhaps more targeted and systematic instructional approaches are needed to change students' habits of mind in the context of physics instruction.

References

D. Kahneman, *Thinking, Fast and Slow* (Farrar, Straus and Giroux, 2011).

J. St. B. T. Evans, *Psychonomic bulletin review*, **13**(3), 378–395 (2006).

E. Amsel, P A. Klaczynski, A. Johnston, S. Bench, J. Close, E. Sadler, and R. Walker, Cognitive Development **23**, 452–471 (2008).

M. Kryjevskaia, M. R. Stetzer, *Phys. Rev. Phys. Educ. Res.,* **10**, 020109, 2014.