CHAPTER 6—COORDINATION PROCESSES

The response patterns presented in chapter four raised several questions about how students judge the realism of animated motions. As a first step in addressing those questions, several causal net elements and two general types of readout strategies were identified in chapter five. In this chapter, the production of students' judgments about computer animations is explored. Special attention is paid to judgments that are apparently inconsistent with students' expectations for realistic motion.

The processes described in this chapter are essentially methods for interpreting students' apparent progression from sets of expectations about realistic motion to identifications of animations depicting realistic motion. When a student accurately makes the readouts implied by the student's expectations, this progression may be straightforward, and the student may make a choice that appears consistent with the student's expectations. In interviews, however, students often chose animations whose features were inconsistent with their expressed expectations for realistic motion. In these cases, connections between students' expectations and choices cannot be so straightforward.

This chapter extends the interview analysis begun in chapter five. In section 6.1, the integration and invariance senses of coordination, described at length in chapter two, are re-described in terms of the present study and the analysis in this chapter. Students' animation choices are compared with expectations for realistic motion in section 6.2; this comparison motivates the search for processes that could explain apparently inconsistent choices. Incorrect readouts are explored as a cause of inconsistent choices in section 6.3. Feedback between readout strategies and the causal net is explored as a cause for inconsistent choices and changes in coordination systems in section 6.4. Processes of coordination are used to explore differences between physics and psychology students' judgments about the [fst] animations in section 6.5. The final section summarizes the major findings of the chapter.

6.1 INTERACTIONS

When a student makes a judgment about the realism of the motion in an animation, it may be understood as the result of interactions among the student's causal net, the student's readout strategies, and the animations. These interactions constitute the student's coordination. The purpose of this chapter is to delineate some particular types of interactions.

DiSessa and Sherin state that "coordination classes include strategies of selecting attention and strategies of determining and integrating observations into the requisite information." This description places emphasis on making useful readouts available for the causal net, and potentially combining observations from several readouts. DiSessa and Sherin describe coordination in the sense of *integration* to emphasize that "within a given situation, multiple observations or aspects may need to be coordinated to determine the necessary information." (diSessa & Sherin, 1998, p.1172). A person with a coordination class, then, could assess a situation, make multiple observations within that situation, and integrate the results to create a single judgment. In the tasks presented here, integration might consist of recognizing and making several different observations about a particular animation in order to judge the realism of the animation's motion. A student with integration problems might base a judgment on the first observation to present itself, rather than using especially reliable observations or integrating information from several different observations. A student with integration problems might also make several observations that lead (through the student's causal net) to conflicting conclusions, leaving the student unable to integrate readouts from the various observations to make a single coherent judgment.

DiSessa and Sherin describe an additional sense of coordination, which they label *invariance*, to emphasize that "across instances and situations, the knowledge that accomplishes readout of information must reliably determine the *same* information. Otherwise we might count the [coordination class] as confused or incoherent." (diSessa & Sherin, 1998, p.1172, emphasis in the original). A person with a coordination class for a particular quantity, then, could reliably determine that quantity in several different circumstances, even if such determinations required the use of different observations and different inferences in different situations. In the tasks presented here, a student who coordinates invariantly should make the same judgments about one-ball and two-ball animations depicting the same motion for the same apparatus, even if those judgments are based on somewhat different features and inferences. A student with invariance problems might make conflicting readouts, or be led to use conflicting causal net elements, in different circumstances.

Judgments are one result of interactions between the causal net and readout strategies. Such interactions may also result in learning--changes in students' coordination systems. "In general, readout strategies and the causal net should co-evolve as learning occurs. There should be episodes of 'conceptual bootstrapping', where causal assumptions drive the learning of new readout strategies. On other occasions, 'noticings'--for example, that something surprisingly affects something else--may drive reformulations in the causal net." (diSessa & Sherin, 1998, p.1177). Most of the evidence in the present study for change in readout strategies or the causal net suggests that the changes were situation specific, and could not in themselves be characterized as useful learning.

6.2 COMPARING CAUSAL NETS WITH CHOICES

Most of the expectations described in chapter five can be related to animation features, in the sense that each animation could be judged to meet or violate each expectation. Students often chose animations apparently incompatible with their expectations. Connections between expectations and animation features are examined in this section. Table 6.1 summarizes the relationships between commonly expressed expectations and animations, indicating (with "NO") which animations contain features apparently incompatible with particular expectations.

	Animation type				
Expectation	*1 [sl]*	*2 [fsl]*	*3 [fst]*	*4 [constvx]*	*5 [real]*
DECELUP (A)				**NO**	
ACCELDOWN (A)	**NO**			**NO**	
CONSTFLAT (A)		flat **NO**	flat **NO**		
DECELFLAT (I)	flat **NO**			flat **NO**	flat **NO**
SAMESPEED (A)	**NO**	**NO**			
NOGAIN (A)		V **NO**	**NO**		
PAUSETOP (I)	V **NO**		V **NO**	V **NO**	V **NO**
TIE (I)	2-ball **NO**	2-ball **NO**			2-ball **NO**
VALLEYWINS (A)	2-ball **NO**	2-ball **NO**	2-ball **NO**	2-ball **NO**	
VALLEYLOSES (I)			2-ball **NO**	2-ball **NO**	2-ball **NO**
MAKEITUP (??)	??	??	??	??	??

Table 6.1 Incompatibilities between animation features and common expectations.

The main features of Table 6.1 can be indicated with specific examples. The "NO" in the DECELUP-[constvx] cell indicates that all four [constvx] animations (one- and two-ball flat- and V-valley) violate the DECELUP expectation, because the ball fails to slow down on the final slope in all four [constvx] animations. The "flat NO" in the CONSTFLAT-[fsl] cell indicates that only the flat-valley [fsl] animations violate the CONSTFLAT expectation; the V-valley [fsl] animations do not violate CONSTFLAT. Each of the race-outcome expectations (TIE, VALLEYWINS, and VALLEYLOSES) can, of course, be incompatible only with two-ball animations; this is indicated with "2-ball NO". The MAKEITUP expectation differs from other expectations in that a student's judgment of whether the ball could reasonably make it up the final slope cannot be objectively evaluated in kinematic or race-outcome terms. MAKEITUP (and other holistic or non-kinematically described expectations expressed by some students) appear to influence students' reasoning about particular animations, but are not systematically useful for comparing expectations described by students with their final choices. This is indicated in the table with question marks, "??". Each expectation listed in Table 6.1 is marked with either an "(A)" or an "(I)", to indicate that it is an Appropriate or Inappropriate expectation for motion on either two-tracks apparatus. (MAKEITUP is not classified as either Appropriate or Inappropriate, as indicated by the question marks.) Only Inappropriate expectations, of course, are violated by features of [real] animations.

A particular student may express expectations that are consistent with only one animation from a set. Such a group of expectations can be described as "well-determining," whether or not the single animation consistent with the expectations is the realistic [real] animation. In contrast, expectations may be "over-determining" or "under-determining." An over-determining group of expectations is inconsistent with all five animations from a set; an under-determining group of expectations is consistent with more than one animation from a set. If a student's causal net is under- or over-determining, even complete knowledge of that student's expectations is not sufficient to predict which animation the student will identify as depicting realistic motion. A student who makes accurate readouts appropriate to a set of expectations that is not well-determining will likely face problems with integration.

Even when a student's causal net is well-determining, the student's expectations and choices may be inconsistent with each other. To illustrate this, consider two quotations from the one-ball V-valley task portion of the interview with Gina, a physics student, as presented in Figure 6.1. In her first statement, Gina expresses the NOGAIN expectation--the ball should not speed up without an apparent cause. In her second statement, Gina's description of why she found [fsl] to be realistic indicates the use of three different expectations: ACCELDOWN, DECELUP, and SAMESPEED. These four expectations are appropriate; Table 6.1 indicates that taken together they are well-determining and compatible only with the [real] animation. Gina chooses the [fsl] animation, however, indicating an apparent mismatch between her expectations and the features of her one-ball V-valley choice. Despite this apparent mismatch, her remarks demonstrate a high level of integration--several readouts about the [fst] and [fsl] animations lead her to the coherent conclusion that the [fsl] motion depicts more realistic motion.

- *"Number 4[fst] it* ***looks like it, stops three-quarters of the way up the V and then accelerates again before it goes over the bump****, so that's wrong."*

  …later in the same task…

- *"I liked number 2[fsl] because it started off to,* ***it started off getting a little bit faster as it went down the first ramp, and then as it went down the V it got a lot faster and as it went up the V it slowed down a little bit, and then when it got to the level part at the end it pretty much had the same speed as the little part of level part at the beginning****.* <Interviewer: And that's good?> *Uh huh.* <Interviewer: Why do you like that, why do you think it's …> *Um, because they're at the same height, so they should have the same speed, pretty much if it's frictionless, or, whatever."*

Figure 6.1 Gina, a physics student, discussing two different one-ball V-valley animations[†].

Taking a student's choices into account implies four categories of expectation/choice comparisons, suggested by the three expectation categories and Gina's example. In a "well-determined" comparison, a student's expectations are compatible only with the animation chosen. Note that "well-determined" does not imply "correct", but rather that expectations expressed by a student appeared to be compatible with only a single animation, which was identified by that student as realistic. In a "differently-determined" comparison, the expectations are compatible with only a single animation, which happens *not* to be the one chosen--as was the case for Gina. In an "under-determined" comparison, the expectations are compatible with more than one animation.

In an "over-determined" comparison, a student's expectations are compatible with no single animation. For all expectation/choice comparison categories except well-determined, some mechanism is needed to explain how a student could have ruled out an animation consistent with expectations, *failed* to rule out an animation *in*consistent with expectations, or both.

The transcript for each of the 36 recorded interviews was coded, statement-by-statement, with the expectations that students appeared to be describing or using to judge an animation. For each student, the set of animations compatible with the coded expectations for each task were determined and compared with that student's choice for the task. See Table 6.2 for the results of these comparisons. (Coding of expectations is necessarily subjective, so these counts provide only rough estimates.) Across all four tasks, only a third of expectation/choice comparisons were well-determined, indicating that in most cases knowledge of the expectations expressed by a student during a task did not provide information sufficient to predict that student's choice in the task. The ratios varied by task; in the one-ball flat-valley task, 69% of expectation/choice comparisons were under-determined; in the two-ball V-valley task, 50% were well-determined.

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† Student quotations in this chapter are formatted to indicate ***readout reports*** and <u>*expressions of expectations*</u> as in chapter five.

Causal net / choice comparison	Percent of all choices
well-determined	33%
differently-determined	17%
under-determined	30%
over-determined	20%

Table 6.2 Causal net / choice comparison for choices in all recorded interviews.

In the majority of small-scale judgments--for example, comparing a readout with an expectation to temporarily rule an animation "in" or "out"--students made successful comparisons. For the most part, students appeared to successfully integrate more than one observation to make a small-scale judgment, as Gina did above. Students appeared to apply expectations such as ACCELDOWN and DECELUP consistently across the four tasks. The consistent use of at least some expectations could be classified as a step toward invariance, although full invariance would obviously result in making the same judgment about each motion in each task. The majority of students' final decisions, however, involved identifying an animation as realistic even though it was apparently incompatible with one or more expectations expressed by the student. Processes that can lead students to judgments apparently incompatible with their expectations are discussed in the following sections.

6.3 INACCURATE READOUTS

Often, in describing their judgments of animations, students reported inaccurate readouts. They had apparently attempted to make readouts appropriate for comparing animation features with expectations, but had failed to make accurate readouts. Readout problems could either lead students to rule out animations consistent with their expectations, or to accept animations as realistic even though the animations were *in*consistent with one or more of their expectations. Presented in section 6.3.1 is a pattern that could lead students with apparently appropriate expectations to rule out a [real] animation as unrealistic. Presented in section 6.3.2 is a pattern that could lead students with apparently appropriate expectations to accept an [fsl] animation as realistic.

6.3.1 Inaccurate readouts limiting choices

When a student's expectations were under- or differently- determined, the student must have ruled out one or more animations apparently compatible with the expectations coded for that student in that task. Because approximately one-half of students' choices in recorded interviews were under- or differently- determined by their coded expectations, a model of student decision-making must provide a method by which this could occur. One possibility is that students could make inaccurate readouts about an animation, and mistakenly determine that the animation violates an expectation.

A particular example of this phenomenon is presented in this section. Several students apparently made inaccurate readouts about the [real] animations and determined that they violated the DECELUP expectation. This example provides a clear case in which students can describe appropriate expectations for realistic motion, but describe inaccurate readouts to rule out a realistic animation. It also provides a model for understanding how so many students with apparently appropriate expectations could rule out the [real] animations.

In Figure 6.2, different students claim that different [real] animations do not depict realistic motion. Four of the five students appeal directly to the DECELUP expectation, claiming that the ball does not slow down on the final slope. For one-ball animations (Sarah and Allison), the claims were necessarily based on fixed-referent readouts. For two-ball animations (Phyllis and Brook), the claims may have been based on fixed-referent or relative motion readouts. In either case, the claims were very similar. In a slight variation, Isaac appeals to the SAMESPEED expectation, claiming that the ball has a different speed on the final shelf than it had on the initial shelf.

- Sarah, psychology, one-ball flat-valley [real]: *"The fifth one* ***gains momentum as it goes down, but it doesn't lose a whole lot, of momentum when it goes up****."*
- Allison, physics, one-ball V-valley [real]: *"That didn't seem to me,* ***there is no deceleration going up the ramp*** *so that's not it"*
- Phyllis, psychology, two-ball flat-valley [real]: *"…****it gained a lot of momentum going down the hill, but it didn't seem to lose any going back up it****."*
- Brook, physics, two-ball V-valley [real]: *"I don't think so because* ***the one that falls down the lowest doesn't seem to slow down it seems to keep its final velocity.****"*
- Isaac, physics, one-ball V-valley [real]: *"the ball here should have the same velocity as it does here.* <Int: So you're pointing to the, the two flat parts.> *Right, 'cause they're at the same level.* ***But they don't****."*

Figure 6.2 Students claiming that [real] animations are unrealistic.

This effect of this particular incorrect readout on excluding consideration of [real] animations for students whose coded expectations were compatible with [real] appeared to be widespread. As shown in Table 6.3, in each of the one-ball tasks, students in more than half of the recorded interviews chose some animation other than [real]. Of those students not choosing [real], more than half expressed expectations that were apparently compatible with [real]. Many of those students apparently followed the pattern described in this section--as shown in the final row of Table 6.3, a large fraction of students with [real]-compatible expectations not choosing [real] reported that ball B failed to slow down on the final slope in the [real] animation. Although students reported similar readouts about speed changes in the two-ball tasks, the high frequency of [real]-compatible expectations was not repeated in the two-ball tasks, where the common TIE expectation was incompatible with [real] animations.

	one-ball flat-valley	**one-ball V-valley**
Of total, students NOT choosing [real]	30 / 36 (83%)	20 / 36 (56%)
Of above, with [real]-compatible Causal Net	21 / 30 (70%)	11 / 20 (55%)
Of above, claimed [real] violated DECELUP	14 / 21 (67%)	8 / 11 (73%)

Table 6.3 Ruling out one-ball [real] animations with inaccurate readouts.

6.3.2 Inaccurate readouts extending choices

When a student's expectations were over- or differently- determined, the student had to choose an animation apparently incompatible with the expectations coded for that student in that task. Because approximately one-third of students' choices in interviews were over- or differently- determined by their coded expectations, a model of student decision-making must provide a method by which this could occur. One possibility is that students could make inaccurate readouts about an animation, and mistakenly determine that the animation does not violate a particular expectation.

A particular example of this phenomenon is discussed in this section. Some students apparently made inaccurate readouts about the one-ball [fsl] animations and determined that they were compatible with SAMESPEED and/or CONSTFLAT expectations. This example provides a clear case in which students describe appropriate expectations for realistic motion but describe inaccurate readouts, and identify an animation depicting unrealistic motion as realistic. It also provides a model for understanding how many students whose expressed expectations were compatible only with the motion in [real] could identify [fsl] animations as depicting realistic motion.

In Figure 6.3, two students claim that one-ball [fsl] animations meet their expectations. Emilio describes appropriate expectations for realistic motion with a mixture of accurate and inaccurate readouts about the one-ball flat-valley [fsl] animation--"picks up speed going down the ramp" (ACCELDOWN, accurate readout); "loses it going up" (DECELUP, accurate readout); "it has the same speed on, um, on this first flat straightaway as the second one" (SAMESPEED, inaccurate readout); and "it's got a constant speed on the middle straightaway" (CONSTFLAT, inaccurate readout). In a similar way, Isaac judges that the one-ball V-valley [fsl] animation meets the ACCELDOWN (accurate readout), DECELUP (accurate readout), and SAMESPEED (inaccurate readout) expectations. Inaccurate readouts enable Emilio and Isaac to judge that the [fsl] animations meet their appropriate expectations for realistic motion.

- Emilio, physics, one-ball flat-valley [fsl]: *"I like 5[fsl] because, um, it* ***picks up speed going down the ramp and loses it going up*** *and it* ***looks like it has the same speed on, um, on this first flat straightaway*** *as the second one,* ***as the ending rather****, and* ***it's got a constant speed on the middle straightaway there****."*
- Isaac, physics, one-ball V-valley [fsl]: *"Well, number 2[fsl], well, what I was looking for in each one, there has to be,* ***some sort of acceleration that's heading downhill, and it's got to decelerate when it's going uphill****, um, similar to the same, like, energy argument that I uh used before, and* ***at points where it's the same, uh at the same point, the velocity would have to be the same****."*

Figure 6.3 Students claiming that [fsl] animations meet their expectations.

6.3.3 Inaccurate readouts and integration

In the examples above, students were led to make judgments that were apparently inconsistent with their expectations. This means that students made inferences based on inaccurate information, but does not necessarily imply that they had difficulty integrating information from several observations to make a coherent conclusion--students in the examples often described several readouts supporting judgments about animations. On the other hand, integration associated with successful coordination sometimes requires the comparison of different readout strategies. Students who based judgments on inaccurate readouts either did not realize that their readout strategies were not sensitive enough to make accurate readouts in some cases, or lacked the knowledge necessary to execute more sensitive readout strategies (for instance, stepping through an animation frame-by-frame in order to infer speed changes from changes in the frame-to-frame distances between ball images).

6.4 FEEDBACK: ADJUSTING READOUTS OR THE CAUSAL NET

Students sometimes rejected all five animations from a set. Having made readouts about every animation that were incompatible with their expectations, they were still required to identify one animation as depicting realistic motion. Students in this situation were left with two options, each involving feedback between readouts and the causal net. They could adjust their causal net so their expectations would be consistent with all readouts about one animation, or they could adjust their readouts about one animation to fit all expectations about realistic motion.

Examples in which students appear to adjust their readouts or their expectations are provided in the following subsections. The examples demonstrate strong interactions between student's readouts and their causal nets, interactions apparently strengthened by their acceptance of the notion that one of the animations presented in the task does in fact depict realistic motion.

6.4.1 Adjusting readouts to fit expectations

Isaac, whose final description of the one-ball V-valley [fsl] animation is presented in Figure 6.3 on page 101, gradually shifted his description of that animation, (in this case, *away* from an accurate description of the [fsl] motion) to fit his expectations for realistic motion. His earlier descriptions, presented in Figure 6.4, differ significantly from his final description of the same animation.

- Isaac, physics, one-ball V-valley [fsl]: *"…**it um accelerates down that, that first part of the V, but it barely gets over,** barely gets over that hump, which wouldn't happen because the uh, the starting point was higher than that, than this point right here, which when it gets to its final flat part."*

  …later, after objecting to all five one-ball V-valley animations…

- Isaac, physics, one-ball V-valley [fsl]: *"Well, going through all of them, it at first didn't seem like, any of them would work, but now looking back at number 2[fsl] again,* ***it accelerates downhill and then decelerates uphill****, but the only point I'm considering is at that point right where the V ends, and it goes over onto the uh flat part.* ***It seems to just barely get over it****, which at first I didn't think would happen, but it still does,* ***but it's not just barely getting over there, it's getting over there with some velocity, too, it's still moving****."*

Figure 6.4 Isaac's early descriptions of the one-ball V-valley [fsl] animation.

In the earliest description, Isaac objects to the ball's motion on the final shelf. By the time he makes the second description in Figure 6.4, Isaac has objected to all five of the one-ball V-valley animations. He points out that the [fsl] animation meets the ACCELDOWN and DECELUP expectations before referring to the troublesome area ("where the V ends") and re-describes the motion at that point in a way that may be closer to full compatibility with his expectations than his first description. In his final description, in Figure 6.3, Isaac has eliminated any question about the realism of the motion. He describes the motion on the final shelf as if it matches the SAMESPEED expectation. It is almost as if Isaac, having decided what he wanted to see, gradually convinced himself that he had seen it.

6.4.2 Adjusting expectations to fit readouts

The episode in which Sarah, a psychology student, reports her decision that the two-ball V-valley [real] animation is realistic demonstrates an apparent shift of expectations to fit the readouts for a particular animation. The episode is presented in Figure 6.5.

- Sarah, psychology, two-ball V-valley [constvx]: *"… **the speed of the ball stays the same the entire time**. You would think it would speed up and slow down."*

  …finally, after rejecting all but the [real] animation…

- Sarah, psychology, two-ball V-valley [real]: "*I think number 3[real] is the most realistic.* <I: Uh huh> *Even though **they end at different places**.* <I: Yeah that bothers you though, right?> *Yeah. But this--it seems like it would, since it's going so fast it's kind of like a ramp effect.* <I: Uh huh> *That makes it go, it doesn't slow down as much because it go- it slants down so severely.* <I: Uh huh> ***It's kind of like a ramp when it flies off and, leaves it going faster.***"

Figure 6.5 Sarah's acceptance of the two-ball V-valley [real] animation.

In her rejection of the [constvx] animation, Sarah clearly expresses the DECELUP expectation. Discussing the [real] animation, she reveals that she has had to adjust two related expectations about realistic motion to determine that [real] is realistic. She has let go of a TIE expectation to accept [real], in which the valley ball wins the race. Her explanation for that change is expressed in terms of another change; the DECELUP expectation does not apply to this particular case in the way she might have expected it to. ("[The ball] doesn't slow down as much because [the track] slants down so severely.") Sarah's label for this phenomenon is "ramp effect", which apparently signifies a relationship between her readouts about the shape of the V-valley track, readouts related to the motion depicted in the [real] animation, and remembered experiences with the motion of real objects.

6.4.3 Feedback, learning, and invariance

Isaac and Sarah, in the examples discussed in this section, appeared to bend their readout strategies or causal nets in order to accept particular animations as realistic. The changes seemed to be localized and situation specific, rather than systematic. It did not appear that the changes would have systematic impacts on their coordination systems that could be considered meaningful learning or conceptual change. The students' coordination systems may have flexible and not highly interconnected, so that systematic change was unlikely.

Tolerance for isolated exceptions to causal nets or readout strategies reduces the chances for invariant coordination. If a student develops a unique readout strategy or expectation to evaluate a particular animation and then reverts to a different set of readout strategies or expectations to evaluate other animations, with no justification for the switch, then there is no way for the student to assure him- or her-self that the same kinds of information have been read out from the different animations.

6.5 A STUDY IN INTEGRATION AND INVARIANCE: [FST] ANIMATIONS

Many students coded with essentially appropriate expectations for realistic motion in the one-ball tasks (ACCELDOWN, DECELUP, NOGAIN, and sometimes CONSTFLAT and/or SAMESPEED) express the expectation that the balls should TIE in at least one of the two-ball tasks. The TIE expectation is, of course, inappropriate for realistic motion on either apparatus. As shown in Table 6.1, the tying two-ball animations ([fst] and [constvx]) are not consistent with all three of the ACCELDOWN, DECELUP, and NOGAIN expectations--[constvx] animations violate ACCELDOWN and DECELUP, and [fst] animations violate NOGAIN. Most of the recorded physics students and several of the recorded psychology students appeared to hold TIE and the other three expectations. As described in chapter four, the [constvx] animations were relatively unpopular and the [fst] animations were much more popular in the two-ball tasks than in the one-ball tasks.

The number of students from each group of interviews who chose the [fst] animation in each task is presented in Table 6.4. Group similarities and differences in the fractions choosing [fst] foreshadow similarities and differences in coordination related to the [fst] motion. The largest differences occurred for the two-ball V-valley task.

Students choosing [fst] animations	one-ball flat	one-ball V	two-ball flat	two-ball V
Physics students (N = 24)	2 (8%)	0 (0%)	19 (79%)	15 (63%)
Psychology students (N = 26)	2 (8%)	0 (0%)	11 (42%)	0 (0%)

Table 6.4 Numbers of interviewed students identifying the [fst] animation as depicting realistic motion in each task.

Trends in how students coordinated readouts and causal net elements related to the one-ball and two-ball [fst] animations are presented in this section. Students' fixed-referent readout strategies for one-ball tasks resulted in different patterns of accurate and inaccurate readouts than did relative motion readout strategies, which were possible only in two-ball tasks. These patterns, central to understanding patterns of student coordination, are discussed in section 6.5.1. Although students from both the psychology and physics classes expressed the expectation that the balls should reach the ends of their tracks simultaneously, physics students provided much more specific reasoning for the TIE expectation than did psychology students. This is discussed in section 6.5.2. Readouts about the [fst] animations made by students from each group are discussed in section 6.5.3. Students' coordination of judgments about the [fst] animations is summarized in terms of integration and invariance in section 6.5.4.

6.5.1 Patterns of success and failure: Fixed-referent and relative motion readout strategies

As described in chapter five, students' readouts of speeds and speed changes in the one-ball animations must have been based on fixed-referent readout strategies. Ball A's presence in the two-ball animations invited the use of relative motion readout strategies. The two types of readout strategies seemed to have somewhat different patterns of success and failure for detecting different types of speed change. These patterns are summarized in Table 6.5, and described below.

Expectation	Fixed-referent readouts	Relative motion readouts
ACCELDOWN	good sensitivity	good sensitivity
DECELUP	poor sensitivity for [real] motions	systematic error for [real] motions
CONSTFLAT	poor sensitivity	poor sensitivity
NOGAIN	good sensitivity for V-valley [fst] motion; otherwise variable across students and animations	poor sensitivity
SAMESPEED	poor sensitivity	systematic error for [real] motions
race outcome	not applicable	good sensitivity

Table 6.5 Patterns of success and failure for Fixed-Referent and Relative Motion readout strategies.

Students neither described nor gave other evidence for awareness of the inferences involved in making fixed-referent readouts. Errors in fixed-referent readouts seemed to be errors of sensitivity. In reference to the DECELUP expectation for the one-ball flat-valley animations, for instance, students routinely reported the accurate observation that [fsl] and [fst] were consistent with DECELUP. The speed change depicted on the final slope of the flat-valley [real] animation was smaller than that in [fsl] and [fst], however, and students routinely *failed* to observe that [real] was consistent with DECELUP. The fixed-referent readout strategies used by many students apparently lacked the sensitivity necessary to resolve the speed change on the final slope for [real]. In a similar way, students' fixed-referent readout strategies were nearly always sensitive enough to detect the NOGAIN violation depicted in the one-ball V-valley [fst] animation. In contrast, several students *failed* to report the NOGAIN violation depicted in the one-ball flat-valley [fst] animation. Some students may simply not have had fixed-referent readout strategies sensitive enough to detect the sudden speed change in the one-ball flat-valley [fst] animation.

When reporting readouts for the two-ball animations, students sometimes indicated awareness that they had used relative ball positions as cues for inferring information about the speed of ball B. Presumably it is easier to judge that one ball is ahead of, tied with, or behind another ball than it is to judge the ball's speed directly. Students were universally successful at making readouts about the race outcome.

Focusing on relative positions during the race, however, seems to have introduced systematic errors into students' readouts about speed changes.

One problem for students using relative motion readouts was that focusing on relative positions may have reduced students' sensitivity to sudden speed changes related to the NOGAIN expectation, because the sudden speed changes depicted in the [fst] motions did not result in sudden changes in the relative positions of the two balls. This may be thought of as a problem with integration. Students took several observations of relative position into account when judging the [fst] motions to make a consistent judgment--demonstrating successful integration. At the same time, the students failed to make use of speed-change information that could have been obtained with other strategies--demonstrating a failure of integration. Differences in integration between students' coordination of the one-ball and two-ball V-valley [fst] animations often resulted in lack of invariance between their judgments of the two animations.

Another set of problems for relative motion readouts was created by students' inferences relating "ahead" to "faster", "tied" to "same speed", and "ball A catching up" to "ball B slowing down." In the animations used for this study, the two balls moved together before ball B entered the valley, so equating "ahead" with "faster" happened to result in appropriate judgments of whether animations were consistent with the ACCELDOWN expectation. In contrast, students' observations and inferences resulted in systematic errors for judging whether or not the two-ball [real] animations were consistent with the DECELUP and SAMESPEED expectations--[real] animations are consistent with the two expectations, but ball A never catches up to ball B. (Note that these problems are not inherent in focusing on relative motion to infer speed changes, but result from the use of inappropriate relationships between relative position and relative speed.) Curiously, lack of sensitivity in fixed-referent readout strategies and systematic error in relative motion readout strategies produced similar (incorrect) DECELUP-related readouts for [real] animations--several students appeared to judge the [real] animations invariantly (but inaccurately) across the one-ball and two-ball situations, even though they employed different readout strategies in the two tasks.

6.5.2 Causal net differences: The TIE expectation

Even among students coded with the TIE expectation, there were characteristic differences between the expectations described by physics students and those described by psychology students. Physics students tended to support the TIE expectation with physics-like reasoning apparently related to energy conservation and the SAMESPEED expectation. Psychology students expressing the TIE expectation tended to be more tentative about it, and not to support it with other reasoning. These differences are illustrated with examples from student transcripts in Figure 6.6 and Figure 6.7.

- Emilio, physics, one-ball flat-valley [fst]: *"…the height is the same, so it gains, um … there's a change in energy from the top to the bottom it should be the same when it gets back up to the top so the speed should the same. I hope. If not I've been doing my entire semester wrong, so …"*
- Emilio, physics, two-ball V-valley [fst]: *"Because when it goes down the ramp, um, it's picking up speed, and when it goes back up the ramp it's losing speed, but it's also at the same time changing height and energy, and so, and that's, one way to find the speed is by the energy of the ball, by finding the, by using height, so when it gets back up to the same height it should have the same energy and speed as it did at the beginning, and since the ball in the back is always at the same height, um, when the ball going up and down the ramp gets to the point where it meets up with the ball in the back it should get there at the same time."*

Figure 6.6 A physics student describing reasoning to support the SAMESPEED and TIE expectations.

Emilio, the physics student whose words appear in Figure 6.6, describes reasoning for the SAMESPEED expectation in the one-ball flat-valley task, saying that the height is the same on each side of the valley (the initial and final shelves), which means that the ball has the same energy on each side of the valley, which means that it should have the same speed on each side of the valley. This is a loose characterization of an energy conservation argument, and Emilio's conclusion (an expression of the SAMESPEED expectation) is appropriate for the situation at hand.

The second excerpt in Figure 6.6 is Emilio's explanation for why the balls should tie, as stated at the end of the two-ball V-valley task. As he had earlier, he connects energy and speed to the ball's height appropriately (although again without a complete argument). Emilio apparently leaps from an (appropriate) SAMESPEED expectation that despite their different paths the two balls should have equal speeds when they have the same elevation to the (inappropriate) TIE expectation that despite their different paths the two balls should be tied in the race when they have the same elevation. This leap is reminiscent of inferences described for students' relative motion readout strategies.

Several physics students described both the SAMESPEED expectation and the TIE expectation in terms similar to Emilio's, essentially substituting the idea of the balls being in the *same place* for the balls having the *same speed*. Most seemed, as Emilio did, to sense a strong connection between expectations about the race outcome and other expectations about realistic motion. Such a connection is inappropriate for this situation: an appropriate energy conservation argument can be used to predict that the balls have the same *speed* (but not necessarily the same position) when they have the same elevation.

- Teresa, psychology, two-ball flat-valley [fst]: "*I think it probably would **roll faster** but then eventually it would have to **slow a little bit going up**, so I think that is why I choose 3[fst].*"

  …and later, in the same task…

- "*I think that they would end up together but I could be wrong.*"

Figure 6.7 A psychology student describing the TIE expectation.

Teresa, a psychology student, expresses the TIE expectation with apparent trepidation in Figure 6.7. She offers a description of what she likes about the two-ball flat-valley [fst] animation, in terms of the ACCELDOWN and DECELUP expectations, but does not describe connections between the TIE expectation and other reasoning. Psychology students who expressed the TIE expectation presented it rather weakly--similar to Teresa's presentation--as a free-standing idea, and not as something strongly integrated with other parts of their causal nets related to realistic motion.

6.5.3 Readout differences: NOGAIN-related readouts

In addition to characteristic differences in causal nets, physics and psychology students coded with the TIE expectation described characteristically different readouts about the two-ball V-valley [fst] animation. Only a small number of recorded physics students reported NOGAIN-related readouts for the two-ball V-valley [fst] animation; the majority of physics students identified the [fst] animation as realistic, reporting readouts related to the ACCELDOWN, DECELUP and TIE expectations, and sometimes the SAMESPEED expectation. Nearly all of the psychology students reported readouts for that animation related to the NOGAIN expectation; they rejected [fst] as portraying unrealistic motion near the end of the final slope. Numbers of recorded physics and psychology students reporting NOGAIN-related readouts for the [fst] animation in each task are shown in Table 6.6.

Counts of NOGAIN-related readouts	**one-ball flat**	**one-ball V**	**two-ball flat**	**two-ball V**
Physics students (N = 12)	7 (58%)	11 (92%)	0 (0%)	3 (25%)
Psychology students (N = 24)	6 (25%)	19 (79%)	1 (4%)	17 (71%)

Table 6.6 Numbers of recorded students reporting NOGAIN-related readouts for [fst] animations in each task.

Physics and psychology students reported characteristically different readouts for the two-ball V-valley [fst] animation, but readouts reported by many students in the two groups for the [fst] animations in the other three tasks were remarkably similar. These similarities and differences are illustrated by transcript excerpts in Figure 6.8 and Figure 6.9. The excerpts presented in Figure 6.8 and Figure 6.9 are typical for interviewed physics students, and for those psychology students who expressed the TIE expectation.

- Isaac, physics, one-ball flat-valley [fst]: "*…it looks like in number 4[fst],* ***it accelerates right at the very en****d*."

- Isaac, physics, one-ball V-valley [fst]: "*It accelerates at,* ***once it gets, it goes down this V and then goes back up, it seems to accelerate right here****.* <I: So just to record, you're pointing about two thirds of the way up this second part of the V.> *Yeah.* ***It seems to slow down and then for some reason it picks up some speed****.*"

- Isaac, physics two-ball flat-valley [fst]: "*… number 2[fst] looks the best, because* ***they start at the same point at the same velocity****, and then when they go to the point where they break,* ***the one that goes downhill accelerates*** *like it should, so* ***it's slightly ahead of the one that's just at constant velocity****. But then* ***at the point where it goes uphill it decelerates and they meet up here and finish at the same time****.*"

- Isaac, physics, two-ball V-valley [fst]: *"… the balls start at the same height and then are released; at the point where they split,* ***the one that goes down the V accelerates so that it um is a little bit ahead*** *of the ball that is on the flat track linearly, but then* ***when it goes up the uh, the uphill part of the V it decelerates again to the point where um, it meets with the the uh ball that was, that was just on the flat track*** *because they have the same um amount of energy and should uh be together because they were at the same height; it doesn't matter that it went down and then went back up, the uh acceleration and deceleration should cancel each other out."*

Figure 6.8 A physics student describes readouts for [fst] animations.

In the first two excerpts in Figure 6.8, Isaac (a physics student) reports NOGAIN-related readouts for both one-ball [fst] animations, commenting on unrealistic speed changes in each. Isaac's descriptions of the flat-valley and V-valley two-ball [fst] animations are similar to each other, and different from his one-ball descriptions. Rather than reporting NOGAIN-related readouts in either two-ball case, he reports readouts related to the balls' relative positions and to the ACCELDOWN, DECELUP, and TIE expectations.

Note that Isaac clearly connects speed-change readouts for the two-ball animations to the relative positions of the two balls when ball B is in the valley and when it reaches the end of the valley: in the flat-valley task, "…accelerates like it should, so it's *slightly ahead* … decelerates and *they meet up here.*…" and in the V-valley task, "accelerates so that it um *is a little bit ahead* … decelerates again *to the point where um, it meets*…." There is no logical problem with Isaac's inference that ball B should move ahead of ball A when its speed increases, since the two balls had equal speeds before the increase in ball B's speed. There is, however, a logical problem with the inference that the distance between the balls should decrease when ball B's speed decreases from a speed higher than ball A's to a speed equal to ball A's; the speed of ball B is always at least as great as that of ball A, so the distance between the two balls should never decrease. (More precisely, the horizontal component of the velocity of ball B is always at least as large as the horizontal component of the velocity of ball A, so the horizontal component of the displacement between the two balls should never decrease.)

Isaac's reasoning about the balls' relative positions after the end of the valley is flawed. His strong expectations about relative positions appear to support the speed change inferences he makes from readouts about relative positions. His readout strategies appear to be focused on verifying that the balls' relative positions at certain points during the race meet his expectations. His readout strategies for the two-ball [fst] animations apparently fail to supply him with information relevant to the NOGAIN expectation.

- Todd, psychology, one-ball flat-valley [fst]: "*I think 1[fst],* ***it starts fast****, and like,* ***only when it reaches the top it slows down*** *like it has a,* ***the speed is increasing all the way*** *and* <u>*I don't think that is correct*</u>*."*
- Todd, psychology, one-ball V-valley [fst]: "*I think* <u>*1[fst] is wrong because it's, before it goes on the flat area again, it cannot go but* ***it is like jumping***</u>*."*
- Todd, psychology, two-ball flat-valley [fst]: *"Ok, I believe that correct is 3[fst] because,* <u>***although they cover the same difference, they cover it differently***</u>*. … Yeah, I would say it is* <u>*3[fst] because the one that goes on a straight line, it only gets some acceleration by going down here, so,* ***it speed, it starts to decrease as it goes to the end*** *but then, but we see the ball that goes, on the curved line, that it will accelerate faster, but then since it loses speed to climb up, they will eventually reach at the same time in the end*</u>*."*
- Todd, psychology, two-ball V-valley [fst]: *"it shows that* ***it has a difficulty in the end****, like again it just,* ***so that it's equal****."*

Figure 6.9 A psychology student describes readouts for [fst] animations.

In the first excerpt in Figure 6.9, Todd (a psychology student) reports an idiosyncratic readout for the one-ball flat-valley [fst] animation, in which he fails to point out the unrealistic speed increase at the end of the final slope. Todd's readout report for the one-ball V-valley [fst] animation is apparently related to the unrealistic speed change near the end of the final slope. Todd's readout reports for the two-ball flat-valley [fst] animation in the third excerpt from Figure 6.9. are remarkably similar to Isaac's reports for the same animation in Figure 6.8, although Todd is not so explicit about making connections between speed changes and relative ball positions as Isaac. Todd reports readouts related to the balls' relative positions at the end of the valley and to the ACCELDOWN, DECELUP, and TIE expectations. For the two-ball V-valley [fst] animation Todd apparently recognizes the unrealistic speed change near the end of the final slope, in sharp contrast to Isaac's identification of this animation as realistic.

6.5.4 Invariance and integration: [fst] judgments

A student with a coordination class useful for judging the realism of motion depicted in the [fst] animations would, by definition, coordinate in a way that integrates several useful observations for each animation and invariantly results in the same judgment for the one-ball and two-ball tasks. Students' attempts to coordinate information about the [fst] animations in the one-ball and two-ball tasks are discussed from the perspective of integration and invariance in this sub-section.

Many physics students describe an appropriate set of expectations for the one-ball tasks (ACCELDOWN, DECELUP, NOGAIN, and sometimes SAMESPEED and/or CONSTFLAT). They describe expectations for realistic motion in the two-ball tasks as if they were similar to the set for one-ball tasks, with the addition of a TIE expectation. Despite the logical inconsistencies between physics students' expectations for the motion of ball B in the valley and the TIE expectation, they seem to have a sense that their causal nets are consistent and well-connected. In fact, they often treat the TIE expectation as if it were equivalent to the SAMESPEED expectation. They also act as if they are discussing equivalent information about speed changes, whether they talk about them in terms of fixed-referent readouts (for one-ball animations) or in terms of the relative motion of two balls. As Isaac's interview demonstrated, this is often not the case; many physics students described violations of the NOGAIN expectation in the one-ball [fst] animations but did not describe those violations, for the same motions, in the presence of the second ball.

Physics students acted as if their two-ball judgements were the same as their one-ball judgments, indicating that they had a sense of invariance across the two tasks. They acted as if they were using the information available in the one-ball and two-ball situations to make coherent judgments about realism of depicted motions, indicating that they had a sense of integrating different observations. In contrast to their apparent sense of invariance, most physics students demonstrated a lack of invariance by making different judgments about the realism of the [fst] animations in the one-ball and two-ball cases. In contrast to their apparent sense of integration, most physics students demonstrated a lack of integration by failing to use the NOGAIN-related information available from fixed-referent readouts to appropriately evaluate the two-ball [fst] animations.

Psychology students who expressed the TIE expectation did not act as if it were closely connected to other parts of their causal net about realistic motion for the two-tracks situations--their sense of having a tightly woven and self-reinforcing causal net for realistic motion in the two-ball animations may not have been as strong as that of many physics students. For the flat-valley tasks, at least, the levels of integration and invariance in these psychology students' judgments of the [fst] animations may have been similar to those of physics students.

Physics students tended to make similar judgments about the two-ball flat-valley and V-valley [fst] animations. In contrast, psychology students tended to make similar judgments for the one-ball and two-ball V-valley [fst] animations. Their V-valley judgments were invariant in a way that physics students' judgments were not. Without a web of reasoning to support the TIE expectation, most psychology students seemed willing to ignore the TIE expectation during the two-ball V-valley task; after all, no single animation fit both the TIE expectation and their other expectations about realistic motion. Their judgments for the two-ball V-valley [fst] animation may not have been well-integrated (although they happened to be correct); psychology students who expected that the balls should tie were forced to *ignore* expectations and readouts related to the race outcome in choosing an animation other than [fst], rather than finding an animation that met their expectations about the race outcome as well as all other expectations. Where physics students apparently made use of readout strategies related to the TIE and SAMESPEED expectations but failed to take NOGAIN-related readouts into account, many psychology students apparently made use of readout strategies related to the NOGAIN expectation but discounted the importance of race outcome-related readouts.

6.6 DISCUSSION

This chapter has been devoted to an exploration of interactions between causal net elements and readouts. Little space went to description of interactions that led to judgments about animated motion that were apparently consistent with students' expectations. This is not because such judgments were rare--in fact, the majority of students' judgments about individual computer animations appeared to be consistent with their expressed expectations. Instead, it is because they are relatively easy to understand. Students most often attempted readouts that would detect motion violating their expectations, and they were often successful.

Most students made some judgments that were apparently inconsistent with their expectations for realistic motion. Against the background of successful judgments, the interactions that led students to inconsistent judgments are especially interesting. Students' choices for each task were the ultimate output of their efforts at coordinating information about each set of computer animations, and inconsistent judgments had a large effect on students' choices.

Judgments that were inconsistent with a students' expectations can be explained by readout problems and by feedback between readouts and the causal net. Inaccurate readouts apparently led students to errors of inclusion and exclusion; sometimes they mistakenly claimed that an animation violated their expectations, and sometimes they *failed* to detect that an animation was inconsistent with their expectations when they should have done so. Students' fixed-referent readout strategies sometimes suffered from a lack of sensitivity. Students using relative motion readout strategies sometimes failed to make use of information that may have been more easily acquired with fixed-referent readout strategies. Students using relative motion readout strategies also made systematically flawed inferences that led them to incorrect conclusions about speed changes for ball B.

Students who had apparently detected expectation violations in every motion from a set sometimes changed their readouts or their expectations in order to accept one animation from the set as realistic. The changes students made appeared to be localized and situation-specific, so that they often resulted in apparent mismatches between the students' expectations and their choices.

When judging the two-ball V-valley [fst] animation, different sorts of interconnections within causal nets appeared to have robust effects on the coordination of information about that animation, and on the judgments made by physics students and psychology students. Physics students appeared to support their TIE expectations with other expectations about realistic motion, and these interconnections in turn appeared to support their consistent use of relative motion readout strategies. Psychology students who expressed the TIE expectation appeared not to have strong interconnections to support it; although they held many expectations in common with the physics students, they made different readouts and different judgments about the animation.