

Finding One's Place in Transfer Space

David Klahr¹ and Zhe Chen²

¹Carnegie Mellon University and ²University of California, Davis

ABSTRACT—“Transfer” is a venerable issue in cognitive development and education. However, its very existence is the subject of extensive debate, and there is as yet no consensus about its definition, measurement, and implications. This article proposes a 3-dimensional conceptual model of transfer distance for thinking about transfer of concepts or strategies in children, and presents some recent findings on children’s transfer of scientific reasoning strategies—task similarity, context similarity, and temporal interval—that exemplify these three dimensions. These studies yield several important and robust findings regarding children’s learning and transfer in problem solving within this model, which provides a valuable organizing framework for objectively measuring transfer distance and for guiding future research in children’s learning.

KEYWORDS—scientific reasoning; children’s learning; transfer space; analogical thinking; models of transfer; problem solving

ISSUES AND DEBATES

“Transfer” is a venerable issue in cognitive development and education. However, there is as yet no consensus about its definition, measurement, and implications (cf. Barnett & Ceci, 2002; Chen & Klahr, 2008; Detterman & Sternberg, 1993; Singley & Anderson, 1989; Thorndike & Woodworth, 1901). Despite the inarguable importance to cognitive development of *long-term transfer*—the application of knowledge acquired years earlier to a current problem—most developmental research has focused on

shorter periods or has not addressed transfer at all. Indeed, an informal keyword analysis of titles and abstracts of the tens of thousands of articles appearing in *Child Development*, *Developmental Psychology*, and *The Journal of Experimental Child Psychology* over the past half century reveals that only approximately 1% of them address transfer per se, and even those few have focused on the application of concepts or strategies to fairly similar problems after short delays and within the same physical and/or social contexts. Researchers have examined children’s transfer in a very wide variety of domains, including memory (Blöte, Resing, Mazer, & Van Noort, 1999; Coyle & Bjorklund, 1997), mathematics (e.g., Alibali, 1999; Goldin-Meadow & Alibali, 2002; Rittle-Johnson, 2006; Siegler & Opfer, 2003), conservation (e.g., Gelman, 1969; Siegler, 1995), understanding of physical rules (Siegler & Chen, 1998), tool use and causal reasoning (Brown & Kane, 1988; Chen, Sanchez, & Campbell, 1997; Chen & Siegler, 2000), scientific reasoning strategies (Klahr & Nigam, 2004; Kuhn, Schauble, & Garcia-Mila, 1992; Schauble, 1990, 1996), computer programming (Klahr & Carver, 1988), analogical mapping (Honomichl & Chen, 2006; Kotovsky & Gentner, 1996; Siegler & Svetina, 2002), transitive inference (e.g., Goswami, 1995), symbolic understanding (Chen, 2007; DeLoache, 2004; Loewenstein & Gentner, 2001; Marzolf & DeLoache, 1994), and theory of mind (Flynn, O’Malley, & Wood, 2004). But for most of these studies, the “transfer distance”—in terms of context and time interval between the original learning and transfer tasks—is quite limited. This is a serious shortcoming, because in order to advance our understanding of how children apply acquired concepts and strategies to novel situations, it is important to focus on *remote transfer* and its theoretical, empirical, and practical implications.

However, the very existence of transfer is the subject of extensive debate (cf. Detterman & Sternberg, 1993). Most of the research over the past century has focused on short-term transfer and has yielded conflicting findings, showing both transfer successes and failures. Although some studies have demonstrated transfer even in young children (e.g., Brown & Kane, 1988; Brown, Kane, & Echols, 1986; Chen & Siegler, 2000), results from laboratory experiments are often counterintuitive, showing

Correspondence concerning this article should be addressed to David Klahr, Department of Psychology, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213; e-mail: klahr@cmu.edu.

© 2011 The Authors

Child Development Perspectives © 2011 The Society for Research in Child Development

DOI: 10.1111/j.1750-8606.2011.00171.x

that not only children but even adults fail to use highly relevant and accessible information. Many studies have reported the narrowness of children's learning and a lack of transfer (e.g., Bransford, Brown, & Cocking, 1999; Cognition and Technology Group at Vanderbilt, 1997; Lave, 1988).

As Dunbar (2001) points out, this leaves our field in the embarrassing situation of having substantial empirical support for results that fly in the face of overwhelming everyday experience. Clearly, cognitive development would be impossible unless children could use what they learn in one context (both temporal and physical) when they encounter relevant tasks in another. But transfer, and remote transfer in particular, is difficult to demonstrate. How can we resolve this paradox? The paucity of empirical studies supporting the existence of remote transfer is due, in part, to the fact that a clear conceptualization of the underlying construct of transfer is, at its core, a vague spatial metaphor having to do with some kind of "distance," but the units of this distance are often subjective and inherently incommensurate. Without understanding the dimensions of transfer, it is impossible to compare the different distances of transfer in a meaningful way. In an influential attempt to address this problem, Barnett and Ceci (2002) suggested that transfer distance involves two taxonomic factors of transfer: *content* and *context*. Content includes the specificity or generality of the learned skills (e.g., transferring procedures or principles), whereas context includes knowledge domain (e.g., biology vs. economics), physical context (school vs. lab), temporal context (time interval), functional context (e.g., academic vs. play), social context (individual vs. group), and modality (e.g., multiple choice vs. essay test).

A CONCEPTUAL MODEL OF TRANSFER DISTANCE

In this article, we propose a three-dimensional framework—adapted from Barnett and Ceci's taxonomy (by separating their "temporal content" from other dimensions and combining their "content" and "knowledge domain")—for thinking about transfer of concepts or strategies in children. We then present some examples of recent studies on children's transfer of scientific reasoning strategies that exemplify these three dimensions. The three aspects of transfer distance in this space are as follows.

1. *Task similarity*: The extent to which the source and target tasks share task features such as *domain* (e.g., mathematical, physics, or social domains), *problem format and materials*, *procedures*, and *cover story*. It is well established that overlapped task features provide cues for spontaneous retrieval of source information and mapping of structural relations between problems (e.g., Brown, 1989; Chen, 1996; Daehler & Chen, 1993; Gentner, Rattermann, & Forbus, 1993; Goswami, 1996).

2. *Context similarity*: The extent to which the contexts of the source and target tasks are similar. Context involves physical and/or social aspects. Physical context refers to the location

where the source tasks are first encountered, whereas social context involves the people and activities associated with that encounter. Either of these two types of contextual similarities may provide retrieval cues when subsequently encountering a relevant problem. For example, Spencer and Weisberg (1986) showed that college students experienced difficulty in solving a problem when the transfer context was different from the learning context, such as transferring from a classroom to a laboratory. Still, only a few studies have addressed the issue of immediate physical and perceptual context in infants and young children's learning (e.g., DeLoache, 2004; Rovee-Collier, 1999), and we know little about the effects of this dimension on children's transfer of problem-solving strategies.

3. *Temporal interval*: The time gap between tasks, which can range from minutes to decades. Research on memory development reveals that increasing temporal delays decreases the ability of infants, toddlers, and older children to recognize or recall prior events (e.g., Bauer, 1997; Ceci & Bruck, 1998; Rovee-Collier, 1999). However, with few exceptions (i.e., Case, 1974; Gelman, 1969), studies rarely explicitly manipulate the time gap between original learning and testing when investigating children's transfer.

Figure 1 depicts a three-dimensional transfer distance space consisting of these three dimensions: task similarity, contextual

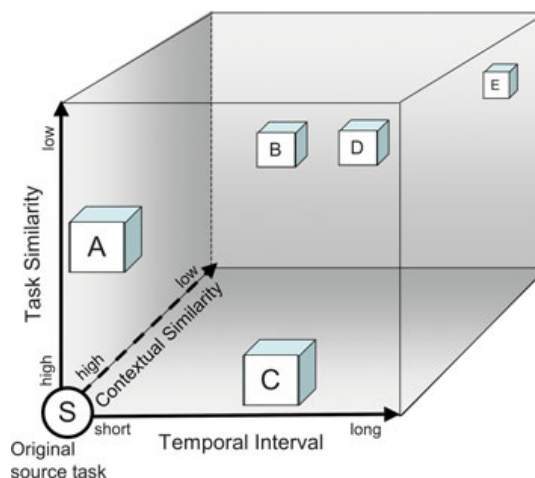


Figure 1. A three-dimensional transfer distance space.

Note. The x-axis corresponds to the *temporal interval* between the learning of the source task and the application of that knowledge to the target task. The y-axis corresponds to the *task similarity* between the source and target. The z-axis corresponds to the *contextual similarity* between the initial learning situation and the transfer situation. Each of the labeled cubes in the space corresponds to a different transfer distance between source and the target. Point A corresponds to the most common form of transfer assessment: high contextual similarity, medium task similarity, and a short temporal interval between training and transfer assessment, whereas Point E represents a transfer task with a long time interval, and substantial differences between source and target tasks and contexts. The other points in the space are described in the text.

similarity, and temporal interval. In this space, the circle at the lower left corner represents a source problem, and the cubes represent target problems at different locations along the three dimensions. Different regions of the space represent transfer distance between source and target. Of course, of the three dimensions, time is the only one that we can measure objectively on a ratio scale. “Distance” measures on the other two dimensions are necessarily arbitrary (e.g., the difference between a “somewhat similar” context and a “highly dissimilar” context). However, recent research in the learning sciences has attempted to create more rigorous and systematic classifications of contextual and task similarity through the concept of “knowledge components” (Cen, Koedinger, & Junker, 2007).

Target Problem A in Figure 1 depicts a typical relation between source and target, in which they differ in superficial task features, but are similar in context (e.g., the lab setting) with short-term delay (e.g., Brown et al., 1986). Problem C depicts a situation in which the source and target are very similar in context and task, but there is a moderate temporal interval (e.g., Rittle-Johnson, 2006). This would correspond, for example, to a typical test–retest situation in an educational context. The relations between the source and other target Problems B, D, and E (e.g., Chen, Mo, & Honomichl, 2004) represent other types of transfer distance between the source and targets. The primary prediction from this model is that the degree of transfer will be proportional to the level of task and contextual similarity between problems and inversely proportional to the temporal interval between the original learning and subsequent assessment. In addition, we hypothesize that these effects will interact with children’s age and the instructional approach being used.

RECENT EMPIRICAL FINDINGS OF TRANSFER IN CHILDREN’S PROBLEM-SOLVING STRATEGIES

Effects of Transfer Distance

The effects of transfer distance on performance are evident in several recent investigations of children’s learning of scientific reasoning strategies.¹

Chen, Mo, Klahr, Tong, Qu, and Chen (2011) examine whether and how 6- to 8-year-old children are able to learn and transfer the fundamental logic of hypothesis testing. The basic task—adapted from Sodian, Zaitchik, and Carey (1991)—involves figuring out a way to test a simple hypothesis by choosing a correct item among three options. Isomorphic versions of this task were presented in different contexts. For example, the “Who sank the boat?” context presented children with a story in

which a fisherman needed to test a hypothesis that the bear who left footsteps around his pond at night was a big (or small) one. The solution involved leaving one of his three boats in the water (the one that a big bear, but not a small bear, could sink). If it is sunken by the morning, a big bear must have done it. The isomorphic tasks shared parallel problem structures and logic, but involved different objects, protagonists, and storylines. The two trials within a context differed in the relations between the bear and the boats. For example, a big bear could sink the medium boat but not the big boat, and a small bear could only sink the small boat on the first trial; on the second trial, a big bear could only sink the big boat, and a small bear could sink the medium and small boats. The early context(s) served as analog(s) for later contexts(s). Each context presented children with a story, and their task was to design an adequate test for a hypothesis.

Children at each age level were assigned to one of three feedback conditions. At the end of each trial, children in the *verbal and physical feedback* condition received verbal instruction and a physical demonstration with props that a big, but not a small bear would sink a specific boat. The verbal instruction illustrated how and why a correct choice would allow one to conclusively test the hypothesis, and the physical demonstration involved showing a correct choice and then an incorrect choice with the props and asking questions concerning why it was a good or bad choice. Children in the *physical feedback* condition received the physical demonstration but no verbal explanation. In the *implicit feedback* condition, children received no explicit instruction, but the experimenter’s systematic and highly specific questions (e.g., asking children why they designed the particular test they did, and asking them if they could “tell for sure” from the test whether the variable they were testing made a difference) served as implicit feedback. Children’s learning and transfer of hypothesis testing strategies were assessed across isomorphic contexts. The study assessed near (within-context), and intermediate (cross-context) transfer when comparing children’s strategy use among the initial and learning phases, and assessed remote transfer in a 12-month-delay posttest in a different context. The posttest involved only the kindergartners and first graders who had participated in the verbal-and-physical and physical-only conditions. Classmates who never participated in the early phases served as a control group.

As Figure 2a reveals, few children were able to generate a conclusive test for the hypothesis on the first task, especially on the first trial, and overall, they improved their performance across the isomorphic contexts. Children learned and transferred the strategies more effectively when they received more intensive and explicit instruction. However, their performance typically followed a staircase pattern (e.g., improvement in performance from Trial A to B within Context 1, and no improvement from Trial B, Context 1 to Trial A, Context 2).

Another aim of this study was to examine whether children who experienced the initial learning tasks were more successful than their peers who did not at solving the posttest problem.

¹We use the authors’ terminology for each of the studies we describe in this article. As a result, similar conditions across different studies have slightly different names. However, most of the studies are straightforward comparisons between highly explicit and teacher-directed instruction and more open-ended exploratory and implicit instruction. This terminological imprecision is an important and contentious issue in its own right (cf. Klahr, 2009, 2010; Klahr & Li, 2005; Tobias & Duffy, 2009), but we do not have space to address it here.

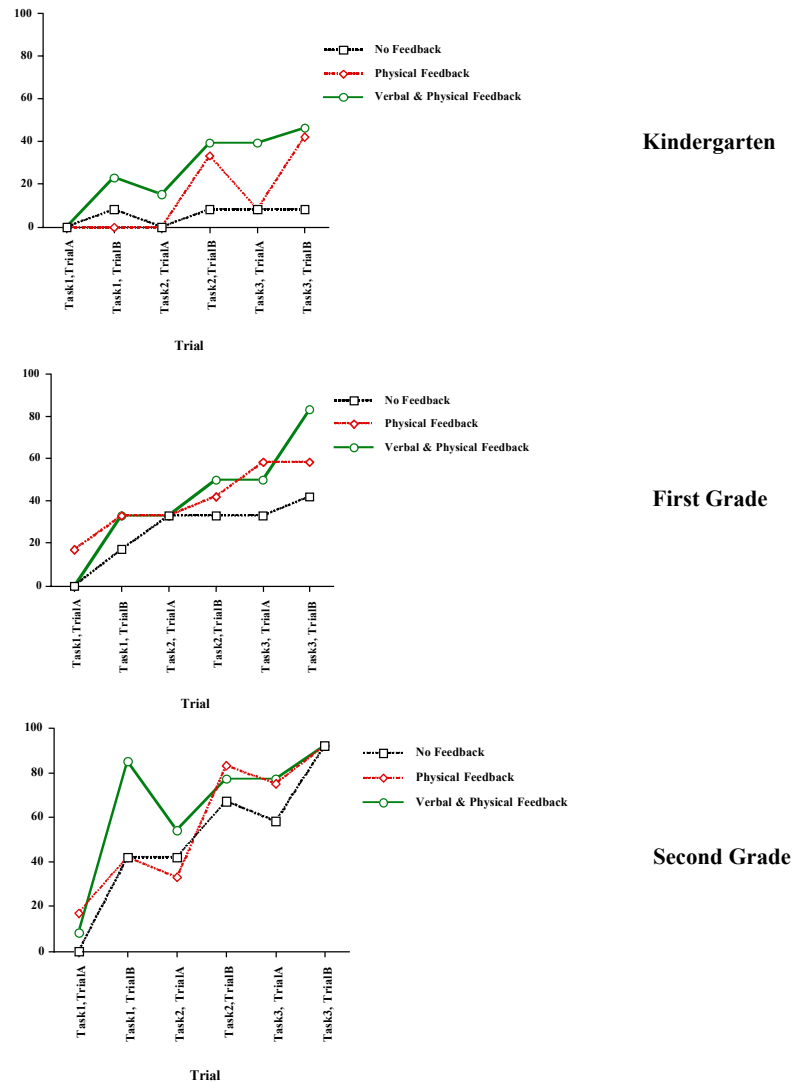


Figure 2a. Percent of children generating conclusive tests of hypotheses on each trial in the test hypotheses study (kindergarten, first grade, and second grade, respectively).

Overall (see Figure 2b), children who participated in the early learning phases outperformed those who had not, indicating that the children, especially the second graders, were capable of transferring the strategies they had learned 12 months earlier—in different contexts and with different tasks—to the posttest. (Note that children in the experimental and control conditions on the posttest received both verbal and physical feedback on each trial, and thus, their performance was predicted to improve over trials on the posttest.) However, when first encountering the posttest task, few first graders in *either* condition spontaneously came up with correct hypothesis tests. Moreover, only about one third of the second graders in the experimental condition used a correct hypothesis testing strategy

on the first trial. This dramatic decrease in performance from the early learning phases indicates that remote transfer is more challenging and less robust than intermediate and near transfer. Findings from other studies that we present below also show a similar pattern of more robust within-task than between-task transfer, and less effective remote transfer than near and intermediate transfer.

Developmental Differences and Transfer Distance

The effect of transfer distance on performance is exacerbated by age differences, as shown in a study in which we investigated elementary school children's learning and transfer of a complex scientific strategy, the control of variables strategy (CVS; Chen

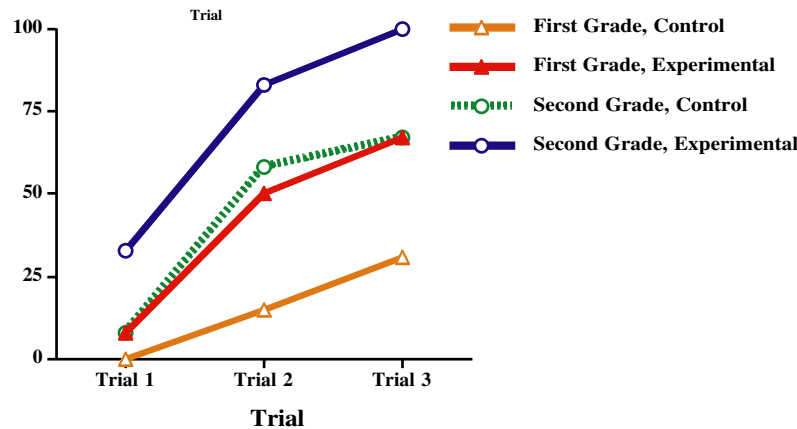


Figure 2b. Percent of children generating conclusive tests of hypotheses on the posttest after a 12-month delay in the test hypotheses study.

& Klahr, 1999). We asked second, third, and fourth graders to design experiments with hands-on, isomorphic materials in three domains (springs & weights, balls & ramps, and sinking objects) to test the possible effects of different variables. We assigned children to three different instructional conditions. Children in the *training–probe* condition received explicit instructions and systematic probe questions about why they designed the test they did for each trial. In the *no training–probe* condition, children received no explicit training, but they did receive the same series of probe questions surrounding each comparison. Children in the *no training–no probe* condition received neither training nor probes. A posttest with paper-and-pencil problems involving domains and a context that were different from the early tasks occurred after a 7-month delay.

Figure 3a illustrates children’s performance in each of the learning phases. The analyses indicated that children—especially those in the *training–probe* condition—increased their performance over phases: They increased the use of CVS from about one third of the trials in the Exploration phase (before training) to nearly two thirds of the trials on the Assessment, Transfer 1, and Transfer 2 phases. Children in the *no training–probe* condition also somewhat outperformed those in the *no training–no probe* condition, who did not significantly improve the use of CVS over phases. Figure 3b shows children’s CVS performance on the posttest, 7 months after initial training. Experimental and control conditions differed in CVS performance at fourth grade, but not third grade. This study reveals clear developmental differences in learning and transfer of scientific reasoning skills. Second graders, like older children, showed within-task transfer; that is, they used CVS within the same task or domain as the initial training. Third graders demonstrated the ability to transfer CVS across problems within the domain of mechanics (when reasoning about the springs, slopes, and sinking tasks). Only fourth graders displayed remote transfer. The pattern of developmental differences in near, intermediate, and

remote transfer is also evident in the studies we present in the next section.

Instructional Approaches and Transfer Distance

Hypotheses about the relations between different instructional approaches and transfer distance are highly controversial (Kirschner, Sweller, & Clark, 2006; Klahr, 2009; Kuhn, 2007; Tobias & Duffy, 2009). Given that far transfer is difficult to achieve, direct instruction and exploratory approaches might yield differential effects, particularly on remote transfer. More direct and explicit instruction might be more effective than discovery learning for remote transfer. On the other hand, direct instruction might be advantageous only for relatively near transfer, whereas mindful and exploratory approaches might be more effective than direct instruction for more remote transfer (Schwartz & Martin, 2004). To address this issue, we describe two studies in which children at different age levels participated in pretest, learning phases, and remote posttest in either direct instruction or exploratory learning conditions. This design enabled us to examine the relative power of these two instructional approaches in near as well as remote transfer.

In one study, we examined 4- and 5-year-old children’s acquisition and transfer of the indeterminacy concept by presenting them with various isomorphic tasks (Klahr & Chen, 2003). We designed the tasks—adapted from Fay and Klahr (1996)—with different materials (e.g., box, stamp, and marker tasks) to explore whether and how children at different age levels transfer the learned strategy from one task to others within the same phase or after a 12-month delay. We presented children with a target object (such as a necklace made from red beads) and a set of three boxes, each of which contained only one type of bead. At the outset of each trial, all boxes were closed, then we opened them sequentially. Prior to the opening of each box, we asked children whether and why they “knew for sure,” or “would have to guess,” about which box was used to construct the necklace.

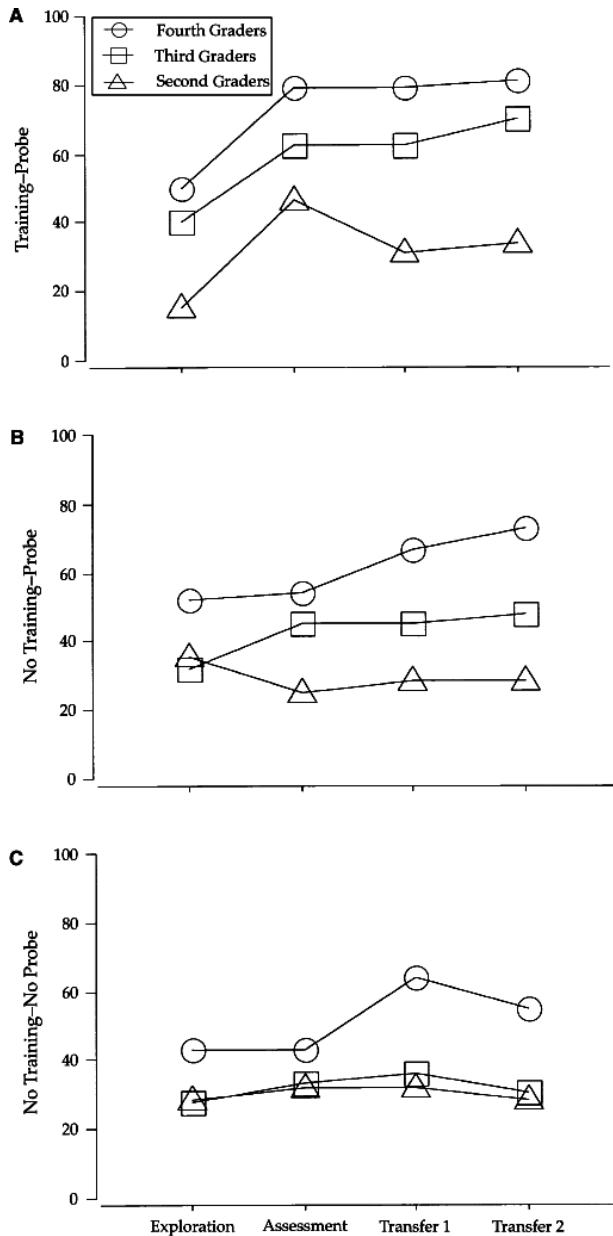


Figure 3a. Percentage of correct control of variables strategy (CVS) usage by condition, phase, and grade in the design experiments study.

Note: “Exploration” phase is the pretest, which was followed immediately by one of the three types of training. “Assessment” phase is the immediate posttest for designing an experiment in the same physical domain as used for the training. “Transfer 1” and “Transfer 2” are CVS assessments a few days after training, in domains other than the training domain. A: Training–probe condition; B: No training–probe condition; C: No training–no probe condition (from Chen & Klahr, 1999, Figure 4).

Consider the “Positive & Hidden” patterns, the evidence pattern in which a single instance is positive (a red bead box is open) and at least one of the remaining boxes is closed. On such prob-

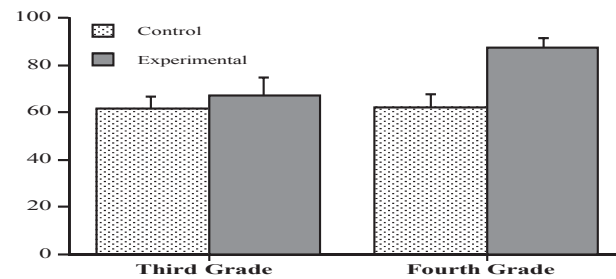


Figure 3b. Percentage of correct answers in posttest in the design experiments study.

lems, children typically incorrectly responded “know” when they should have said “guess” because one or both of the remaining boxes could have also contained matching (red) beads from which the necklace was made. Fay and Klahr called this the “positive capture” strategy because the single positive instance seemed to capture children’s attention and, in effect, blinded them to the fact that the unexplored options might yet render the problem indeterminate.

The study demonstrated robust transfer in the learning of scientific process strategies. Both 4- and 5-year-olds initially experienced difficulty in solving the tasks, especially the Positive & Hidden patterns, but improved their performance after experiencing an analogous source task, as Figure 4 shows. Although the positive capture strategy is a robust phenomenon in young children’s reasoning, 5-year-olds, and 4-year-olds to a lesser extent, were capable of transferring the reasoning strategy they acquired from an original learning context. Children’s relatively near transfer (the learning phases) but not remote transfer (posttest) benefited more from the training (explicit feedback) condition than the control (implicit feedback) condition. In particular, when children in the two conditions encountered the first trial of the posttest, their performance was virtually the same.

In another study, Strand-Cary and Klahr (2008) extended the Chen and Klahr (1999) investigation of CVS training (which we described earlier) by including additional measures and temporal delays between training and assessment in comparing the effects of two different levels of explicitness during instruction, on third, fourth, and fifth graders’ ability to learn CVS. Here, we focus on only one aspect of Strand-Cary and Klahr to illustrate the utility of the transfer space we described earlier. The initial instruction—either highly structured (explicit) or very nondirective (exploratory)—used the ramps apparatus we described earlier. The first assessment measure took place immediately after the training, and the second assessment took place 3 months later. Training and both assessments used the same ramp materials, but the particular aspect of ramps being investigated during the assessments included both the initially trained feature (length of the ramp) and some previously uninvestigated features (surface or height of ramp). Thus, the two assessments represent two

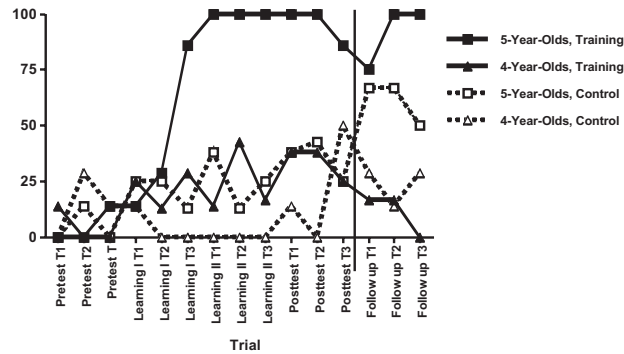


Figure 4. Percentage of correct responses to “Positive & Hidden” evidence patterns on each trial during pretest, learning, posttest, and follow-up trials, in the distinguish determinacy study.

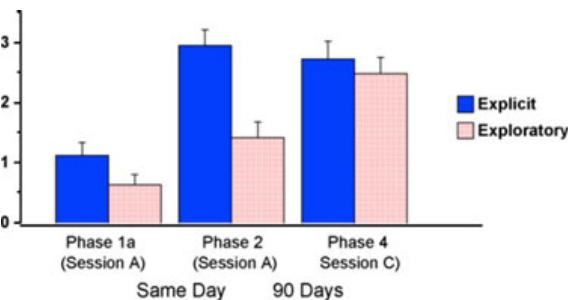


Figure 5. Near and far transfer on scientific reasoning task, maximum score = 4 (from Figure 4, Strand-Cary & Klahr 2008).

different points in time in the Temporal Interval dimension in Figure 1, but they are similarly close to the source in terms of task and contextual dimensions.

In Figure 5, Phase 1a shows performance of children in the two training groups prior to training, and Phases 2 and 4 show their performance immediately following training and 3 months later, respectively. It is clear that explicit instruction had an immediate advantage over exploration, but this advantage disappeared over the 3-month delay, at which point, both groups reached equivalent levels of CVS performance. These findings are consistent with the Klahr and Chen (2003) study, revealing the same interesting phenomenon of delayed effects of exploration instructional methods on more remote transfer.

CONCLUSIONS AND FUTURE DIRECTIONS

The aim of this brief summary of some recent investigations of children’s transfer of problem-solving and scientific reasoning strategies is to describe some new ways to conceptualize and operationalize the elusive construct of “transfer distance.” We have described a number of studies that examine how different instructional approaches affect different types of transfer in chil-

dren at different ages. These studies yield several important and robust findings regarding children’s learning and transfer in problem solving within the present transfer distance framework. First, the transfer distance between problems predicts the degree of transfer performance (Chen & Klahr, 1999; Chen et al., 2011; Klahr & Chen, 2003). Second, with age, children are increasingly capable of transferring learned concepts or strategies to more remote situations (Chen & Klahr, 1999; Chen et al., 2011; Klahr & Chen, 2003). In other words, younger children show robust relatively near transfer, whereas older children demonstrate more remote transfer. Third, more direct and explicit instruction proves to be particular advantageous for relatively near transfer, whereas mindful and exploratory approaches are sometimes equally effective for more remote transfer (Klahr & Chen, 2003; Strand-Cary & Klahr, 2008). That is, as transfer distance increases, the immediate advantage of direct instruction over discovery learning is diminished, and the two methods may become equally effective in facilitating remote transfer. The analyses of transfer distance within this framework, and the relations between transfer distance and age differences in transfer performance and effects of various instructional approaches, have both significant theoretical and educational implications and warrant further investigation.

These studies are only initial steps in exploring remote transfer in children. With the “rebirth” of research on children’s learning (Siegler, 2000, 2006), we are beginning to see more studies investigating children’s transfer and generalization of strategies, and research on near and remote transfer is beginning to flourish. One fruitful avenue for further study is to explore how to promote optimal remote transfer and to pinpoint exactly how different instructional approaches facilitate various types of transfer. Furthermore, although developmental differences in transfer are evident, the mechanisms underlying those age differences remain to be explored. Although the studies we described above have begun to shed light on the relations between instructional approaches and children’s transfer of scientific reasoning strategies at different transfer distances, additional studies must systematically manipulate the three dimensions of transfer distance depicted in Figure 1. Despite the incommensurate nature of the different dimensions, this conceptual model nevertheless provides a valuable organizing framework for objectively measuring transfer distance and for guiding future research in children’s learning.

REFERENCES

- Alibali, M. W. (1999). How children change their minds: Strategy change can be gradual or abrupt. *Developmental Psychology*, 35, 127–145.
- Barnett, S. M., & Ceci, S. J. (2002). When and where do we apply what we learn? A taxonomy for far transfer. *Psychological Bulletin*, 128, 612–637.
- Bauer, P. J. (1997). Development of memory in early childhood. In N. Cowan (Ed.), *The development of memory in childhood. Studies in*

- developmental psychology* (pp. 83–111). Hove, UK: Psychology Press/Erlbaum.
- Blöte, A. W., Resing, W. C. M., Mazer, P., & Van Noort, D. A. (1999). Young children's organizational strategies on a same-different task: A microgenetic study and a training study. *Journal of Experimental Child Psychology*, 74, 21–43.
- Bransford, J. D., Brown, A. L., & Cocking, R. R. (1999). *How people learn: Brain, mind, experience, and school*. Washington, DC: National Academy Press.
- Brown, A. L. (1989). Analogical learning and transfer: What develops? In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning* (pp. 369–412). Cambridge, UK: Cambridge University Press.
- Brown, A. L., & Kane, M. J. (1988). Preschool children can learn to transfer: Learning to learn and learning from example. *Cognitive Psychology*, 20, 493–523.
- Brown, A. L., Kane, M. J., & Echols, C. H. (1986). Young children's mental models determine analogical transfer across problems with a common goal structure. *Cognitive Development*, 1, 103–121.
- Case, R. (1974). Structures and strictures: Some functional limitations on the course of cognitive growth. *Cognitive Psychology*, 6, 544–574.
- Ceci, S. J., & Bruck, M. (1998). The ontogeny and durability of true and false memories: A fuzzy trace account. *Journal of Experimental Child Psychology*, 71, 165–169.
- Cen, H., Koedinger, K. R., & Junker, B. W. (2007). Is over practice necessary? Improving learning efficiency with the cognitive tutor through educational data mining. In R. Luckin, K. Koedinger, & J. Greer (Eds.), *Artificial intelligence in education—Building technology rich learning contexts that work* (pp. 511–518). Amsterdam, Netherlands: IOS Press.
- Chen, Z. (1996). Children's analogical problem solving: Effects of superficial, structural, and procedural similarity. *Journal of Experimental Child Psychology*, 62, 410–431.
- Chen, Z. (2007). Learning to map: Strategy discovery and strategy change in young children. *Developmental Psychology*, 43, 386–403.
- Chen, Z., & Klahr, D. (1999). All other things being equal: Acquisition of the control of variables strategy. *Child Development*, 70, 1098–1120.
- Chen, Z., & Klahr, D. (2008). Bridging the gap: Remote transfer of problem-solving and scientific reasoning strategies in children. In R. Kail (Ed.), *Advances in child development and behavior* (Vol. 36, pp. 419–470). Burlington, MA: Academic Press.
- Chen, Z., Mo, L., & Honomichl, R. (2004). Having the memory of an elephant: Long-term retrieval and use of analogues in problem solving. *Journal of Experimental Psychology: General*, 133, 415–433.
- Chen, Z., Mo, L., Klahr, D., Tong, X., Qu, C., & Chen, H. (2011). *Learning to test hypotheses: Kindergartners and elementary school children's acquisition of scientific reasoning strategies*. Manuscript in preparation.
- Chen, Z., Sanchez, R. P., & Campbell, T. (1997). From beyond to within their grasp: The rudiments of analogical problem solving in 10- and 13-month-olds. *Developmental Psychology*, 33, 790–801.
- Chen, Z., & Siegler, R. S. (2000). Across the great divide: Bridging the gap between understanding of toddlers' and older children's thinking. *Monographs of the Society for Research in Child Development*, 65(2, Serial No. 261).
- Cognition and Technology Group at Vanderbilt. (1997). *The Jasper project: Lessons in curriculum instruction, assessment, and professional development*. Mahwah, NJ: Erlbaum.
- Coyle, T. R., & Bjorklund, D. F. (1997). Age differences in, and consequences of, multiple- and variable-strategy use on a multitrial sort-recall task. *Developmental Psychology*, 33, 372–380.
- Daehler, M. W., & Chen, Z. (1993). Protagonist, theme, and goal object: Effects of surface features on analogical transfer. *Cognitive Development*, 8, 211–229.
- DeLoache, J. S. (2004). Becoming symbol-minded. *Trends in Cognitive Sciences*, 8, 66–70.
- Detterman, D. K., & Sternberg, R. J. (1993). *Transfer on trial: Intelligence, cognition, and instruction*. Norwood, NJ: Ablex.
- Dunbar, K. (2001). The analogical paradox: Why analogy is so easy in naturalistic settings, yet so difficult in the psychology laboratory. In D. Gentner, K. J. Holyoak, & B. Kokinov (Eds.), *Analogy: Perspectives from cognitive science* (pp. 314–334). Cambridge, MA: MIT Press.
- Fay, A., & Klahr, D. (1996). Knowing about guessing and guessing about knowing: Preschoolers' understanding of indeterminacy. *Child Development*, 67, 689–716.
- Flynn, E., O'Malley, C., & Wood, D. (2004). A longitudinal, microgenetic study of the emergence of false belief understanding and inhibition skills. *Developmental Science*, 7, 103–115.
- Gelman, R. (1969). Conservation acquisition: A problem of learning to attend to relevant attributes. *Journal of Experimental Child Psychology*, 7, 167–187.
- Gentner, D., Rattermann, M. J., & Forbus, K. D. (1993). The roles of similarity in transfer: Separating retrievability from inferential soundness. *Cognitive Psychology*, 25, 524–575.
- Goldin-Meadow, S., & Alibali, M. W. (2002). Looking at the hands through time: A microgenetic perspective on learning and instruction. In N. Granott & J. Parziale (Eds.), *Microdevelopment: Transition processes in development and learning* (pp. 80–105). New York: Cambridge University Press.
- Goswami, U. (1995). Transitive relational mappings in three- and four-year-olds: The analogy of goldilocks and the three bears. *Child Development*, 66, 877–892.
- Goswami, U. (1996). Analogical reasoning and cognitive development. In H. W. Reese (Ed.), *Advances in child development and behavior* (pp. 91–138). San Diego, CA: Academic Press.
- Honomichl, R. D., & Chen, Z. (2006). Learning to align relations: The effects of feedback and self-explanation. *Journal of Cognition and Development*, 7, 527–550.
- Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist*, 41, 75–86.
- Klahr, D. (2009). "To every thing there is a season, and a time to every purpose under the heavens": What about direct instruction? In S. Tobias & T. M. Duffy (Eds.), *Constructivist theory applied to instruction: Success or failure?* (pp. 291–310). New York: Taylor & Francis.
- Klahr, D. (2010). Coming up for air: But is it oxygen or phlogiston? A response to Taber's review of "Constructivist instruction: Success or failure?" *Education Review*, 13(13). Retrieved February 9, 2011, from <http://www.edrev.info/essays/v13n13.pdf>
- Klahr, D., & Carver, S. M. (1988). Cognitive objectives in a LOGO debugging curriculum: Instruction, learning, and transfer. *Cognitive Psychology*, 20, 362–404.
- Klahr, D., & Chen, Z. (2003). Overcoming the positive-capture strategy in young children: Learning about indeterminacy. *Child Development*, 74, 1275–1296.

- Klahr, D., & Li, J. (2005). Cognitive research and elementary science instruction: From the laboratory, to the classroom, and back. *Journal of Science Education and Technology*, 4, 217–238.
- Klahr, D., & Nigam, M. (2004). The equivalence of learning paths in early science instruction: Effects of direct instruction and discovery learning. *Psychological Science*, 15, 661–667.
- Kotovsky, L., & Gentner, D. (1996). Comparison and categorization in the development of relational similarity. *Child Development*, 67, 2797–2822.
- Kuhn, D. (2007). Is direct instruction an answer to the right question? *Educational Psychologist*, 42(2), 109–113.
- Kuhn, D., Schauble, L., & Garcia-Mila, M. (1992). Cross-domain development of scientific reasoning. *Cognition & Instruction*, 9, 285–327.
- Lave, J. (1988). *Cognition in practice: Mind, mathematics and culture in everyday life*. New York: Cambridge University Press.
- Loewenstein, J., & Gentner, D. (2001). Spatial mapping in preschoolers: Close comparisons facilitate far mappings. *Journal of Cognition and Development*, 2, 189–219.
- Marzolf, D. P., & DeLoache, J. S. (1994). Transfer in young children's understanding of spatial representations. *Child Development*, 65, 1–15.
- Rittle-Johnson, B. (2006). Promoting transfer: Effects of self-explanation and direct instruction. *Child Development*, 77, 1–15.
- Rovee-Collier, C. (1999). The development of infant memory. *Current Directions in Psychological Science*, 8, 80–85.
- Schauble, L. (1990). Belief revision in children: The role of prior knowledge and strategies for generating evidence. *Journal of Experimental Child Psychology*, 49, 31–57.
- Schauble, L. (1996). The development of scientific reasoning in knowledge-rich contexts. *Developmental Psychology*, 32, 102–119.
- Schwartz, D. L., & Martin, T. (2004). Inventing to prepare for future learning: The hidden efficiency of encouraging original student production in statistics instruction. *Cognition and Instruction*, 22, 129–184.
- Siegler, R. S. (1995). How does change occur: A microgenetic study of number conservation. *Cognitive Psychology*, 28, 225–273.
- Siegler, R. S. (2000). The rebirth of children's learning. *Child Development*, 71, 26–35.
- Siegler, R. S. (2006). Microgenetic analyses of learning. In W. Damon & R. M. Lerner (Series Eds.) & D. Kuhn & R. S. Siegler (Vol. Eds.), *Handbook of child psychology: Vol. 2. Cognition, perception, and language* (6th ed., pp. 464–510). Hoboken, NJ: Wiley.
- Siegler, R. S., & Chen, Z. (1998). Developmental differences in rule learning: A microgenetic analysis. *Cognitive Psychology*, 36, 273–310.
- Siegler, R. S., & Opfer, J. E. (2003). The development of numerical estimation: Evidence for multiple representations of numerical quantity. *Psychological Science*, 14, 237–243.
- Siegler, R. S., & Svetina, M. (2002). A microgenetic/cross-sectional study of matrix completion: Comparing short-term and long-term change. *Child Development*, 73, 793–809.
- Singley, M. K., & Anderson, J. R. (1989). *The transfer of cognitive skill*. Cambridge, MA: Harvard University Press.
- Sodian, B., Zaitchik, D., & Carey, S. (1991). Young children's differentiation of hypothetical beliefs from evidence. *Child Development*, 62, 753–766.
- Spencer, R. M., & Weisberg, R. W. (1986). Context-dependent effects on analogical transfer. *Memory & Cognition*, 14, 442–449.
- Strand-Cary, M., & Klahr, D. (2008). Developing elementary science skills: Instructional effectiveness and path independence. *Cognitive Development*, 23, 488–511.
- Thorndike, E. L., & Woodworth, R. S. (1901). The influence of improvement in one mental function upon the efficiency of other functions: Functions involving attention, observation and discrimination. *Psychological Review*, 8, 553–564.
- Tobias, S., & Duffy, T. M. (Eds.). (2009). *Constructivist theory applied to instruction: Success or failure?* New York: Taylor & Francis.