Children's Analog and Digital Clock Knowledge

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FRIEDMAN, WILLIAM J., and LAYCOCK, FRANK. Children's Analog and Digital Clock Knowledge. CHILD DEVELOPMENT, 1989, 60, 357-371. Understanding the clock system requires knowledge of several distinct components, including reading displays, transforming times, and understanding their temporal referents. 2 experiments were conducted to determine the ages at which children can read and transform times given in analog and digital displays, can link times to activities, and can judge the order of hours in the day. Altogether, 240 children from first to fifth grades were tested. Digital time reading was well developed by the first grade. Analog time reading was equivalent only for whole-hour problems, with some other times proving difficult even for the oldest children. However, there was no overall digital advantage for tasks requiring the addition of 30 min, and the relative difficulty of analog and digital displays varied by problem type. Reported methods indicated that children used a number of different processes in solving the problems. In spite of the gradual development of reading and transformation skills, even the youngest children knew the times of many activities and understood the order in which daily activities occur. However, clock times were not incorporated in the earliest representations of the order of daily events.

The clock system is important in the lives of children from the preschool years onward, but it is probably the least studied of the major symbol systems that confront children. This relative lack of research may be due in part to a failure to segregate clock knowledge from other aspects of time knowledge that have been studied (Friedman, 1982). In this study we attempt to raise and answer a number of basic questions about the development of clock knowledge in children.

In spite of the apparent integrity of the clock system, there are a number of distinct components of clock knowledge. First, there is the obvious ability to look at a clock and read the time. Second, there is the ability to operate on clock times to extract relationships. Just as arithmetic operations are key to the understanding of number, so the ability to determine what the time will be in 15 min or how long it is until 2:00 are essential parts of understanding the clock system. Third, there is the understanding of the meanings of times, such as the knowledge of "where" a given clock time falls within a day or what activities typically occur at that time.

This multiplicity of components allows us to study what happens when children confront an ecologically important but complex symbol system. If the representations and processes that eventually capture different components make different capacity demands or require different amounts of practice, we may find considerable disparities in the ages at which the components are acquired. Thus, what we intuitively consider to be a single content would be mastered piecemeal.

The first component, reading clock times, itself appears to involve multiple processes, and these processes seem to differ considerably for analog and digital clock displays. Analog clocks represent hours on a continuum in which numerals and the succeeding intervals are interpreted as discrete steps from 1 to 12. Minute values are indicated by a separate but superimposed scale ranging from 1 to 60. In principle, people who can read clocks might store an associated time name for each configuration and use retrieval processes (Siegler & Shrager, 1984) to read the display. But there are 720 different times to the exact minute, so such a representation, while allowing rapid performance, would require considerable memory resources. Instead most individual times are probably read by means of a self-terminating series of operations, operations that correspond to the procedures that children are taught. These include attending to the numeral to which the hour hand points or,
if necessary, has passed most recently to get
the hour value, determining the minute value by
counting clockwise by 5s from the top of
the clock face until the 5-min mark pointed to
or immediately preceding the minute hand
pointing is reached, and, if necessary, count-
ning the remaining hash marks by 1s.

The processes, of course, should vary ac-
cording to the specific times that are dis-
played and might also be expected to change
in certain ways with practice. For example,
children probably quickly learn to associate
time names with certain “landmark” point-
ings such as “o’clock” with the minute hand
pointing to the 12 and “30” with the minute
hand pointing to the 6. These associations
eliminate the need to count 5-min marks.
With repetition, children probably come to
recognize additional 5-min multiples directly
and to use their values as starting points for
other 5-min and 1-min increments. Such asso-
ciations presumably become a component of
what remains for most times a sequence of
operations.

Reading digital clocks would appear to
involve quite different processes. Because
hour and minute values are shown as numer-
als, they can be read like any other 1- and 2-
digit numbers, as long as one possesses this
skill and knows that the colon is used to parti-
tion the hour value and the minute value, that
:00 displays are read as “o’clock,” and that a
zero in the 10s place to the right of the colon
is read as “oh.” Performance seems mainly a
matter of retrieving number names, so there
should be little variation from problem to
problem and little change in the processes
with practice. In general, number retrieval
seems to make fewer processing demands
than the mental procedural sequences that we
have assumed underlie most analog clock
reading problems. Therefore, even given sim-
ilar exposure and training, we would expect
digital clock reading to reach skilled levels
before analog clock reading, with the possible
exception of whole-hour analog times.

The second component of clock knowl-
edge may show less divergence between ana-
log and digital clocks. Operations on clock
times, such as adding some interval to the
present time, probably depend to a consider-
able extent on mental procedural sequences
for both display types, with direct retrieval
playing a minor role. Given the large number
of possible starting times and intervals to be
added or subtracted, prestorage of answers
seems infeasible. However, the particular
procedures involved may be influenced by
the type of display. For example, imagined
minute hand movements may be used to add
or subtract some interval from an analog dis-
play, whereas digital displays may be more
likely to invoke numerical addition or sub-
traction. Also, people who have had consid-
erable experience with analog clocks might use
mental images of minute hand movements to
perform many operations on digitally dis-
played times. Finally, for both display types,
certain problems may come to be solved by
retrival-like processing. Problems involving
adding or subtracting half an hour from
whole-hour or half-hour times may be en-
countered frequently enough that operations
become automatized, direct associations de-
velop, or children learn to apply their mathemat-
cal knowledge about adding halves. Ac-
ccordingly, we might expect that as children
grow older they come to solve such problems
rapidly, whereas most other problems, both
analog and digital, continue to require rela-
tively long solution times.

The third component of clock knowledge
is understanding the referents of clock times.
There are at least two levels at which this
correspondence might be understood. One is
knowing the usual times of activities. This in-
formation could be coded by representations
as simple as paired associations between time
names and activities. The other is knowing
the temporal “location” of a clock time within
a day or the daily order of clock times. This
information would seem to require richer rep-
resentations, such as associative networks, se-
rial structures, or images (see Friedman, in
press).

Given this distinction, children could
learn isolated links between particular times
and activities before they possess an overall
scheme for the order of clock times, just as
they might know the month of their birthday
before understanding the order of the months.
However, it is difficult to predict when tem-
poral structures come to be represented be-
cause previous research has shown some rep-
resentations to be present by early childhood
(e.g., Friedman, 1977; Muto, 1982; Nelson,
1986), whereas others are acquired between
middle childhood and adolescence (Fried-
man, 1986). The age of acquisition may de-
pend on the number of repetitions of the tem-
poral pattern that have been experienced and
the number of elements in the structure. Chi-
ldren, of course, have encountered hundreds
of repetitions of the daily cycle by the time
they begin school. However, it is unclear
whether clock times are incorporated in their
first representations of daily time patterns or
whether the times are added to what are initially activity-based representations.

The present study was designed to provide information about when children come to understand the three components of the clock system. Unlike other studies which focus principally on analog clock reading skills (Case, Sandieson, & Dennis, 1986; Siegler & McGilly, in press; Springer, 1952), we tested the same samples of children on comparable analog and digital clock tasks. These comparisons allow us to separate reading skills, which according to our analysis are likely to differ substantially for the two clock types, from operation skills, which are likely to involve complex procedural sequences for both. In addition, we determined the ages at which children can link clock times to daily activities and the ages at which they can order a series of times defined by hour readings and a series defined by activities. These tasks all pertain to the meaning of times, but some could be answered by accessing isolated associations, whereas others require the ability to interrelate a set of times.

Experiment 1

In the first experiment, we examined age differences in children's ability to use analog and digital displays. We tested 160 children from first through fifth grades in two different school districts. To measure detection ability, we presented each child with pictures of analog and digital clocks and asked them to tell the time. In the transformation tasks, we asked them to tell what the time would be in 30 min. When the face was displayed it was named, so that transformation ability could be separated from detection ability. To learn about the processes underlying performance on the detection and transformation tasks, we analyzed children's errors and reported methods in addition to their accuracy. To about one-third of the subjects we also gave an optional transformation task in which they were asked to directly compare their methods for solving analog and digital problems.

Method

Subjects

Thirty-two children from each of grades 1–5 participated in the study. Half at each grade came from a suburban school in New Jersey and half from a school near a large city in upstate New York. The sample was evenly divided by sex at each grade. Mean ages for the five grades are 6.6, 7.7, 8.6, 9.7, and 10.6.

Procedure

Each child was given the following tasks, which were administered in the order listed below, nearly all in a single session of about 30 min. The optional transformation task was only given to the children from one school because of time limitations, and in this school only 61 out of 80 children had time for this task during the authorized session length (8, 12, 11, 15, and 15 children from grades 1–5, respectively). One child in each sex, grade and school combination was assigned to each of eight stimulus orders. On any given task, half of the children received digital problems before analog problems. For half of the children, the order of analog and digital presentation was the same in the detection and transformation tasks. The optional transformation task always had the opposite order for analog and digital problems as the main transformation task. In each task, half of the subjects received digital problems based on the hour 4:00 and half on the hour 8:00. Analog problems in each task had the reverse assignment.

Detection task.—Three analog and three digital stimuli were presented: 4:00, 4:30, and 4:43 for one display type, and 8:00, 8:30, and 8:43 for the other. The three problem types were selected to represent increasing levels of complexity in the application of analog reading procedures. The X:00 problems use a direct hour hand pointing and a minute hand landmark. The X:30 problems require application of the passed hour rule for the hour hand and recognition of a minute hand landmark or the use of 5-min multiple increments. The X:43 problems involve passed hour, 5-min multiple increment, and 1-min increment procedures. Order of the three problem types varied randomly across the eight stimulus orders. Stimuli were 8 x 9-cm cards. Analog stimuli consisted of 6-cm-diameter clock faces, with 5-min marks labeled with numerals and hands of 2.5 and 1.8 cm. The usual hash marks indicated 1-min values. Digital stimuli were 1.5-cm-high block numerals separated by a colon and enclosed in 4.5 x 2.4-cm rectangles.

General instructions for the detection tasks were, "I'm going to show you some times using pictures of clocks. For each one tell me what time it says. Also tell me as you go along how you are figuring out the answer. Please tell me everything you are thinking for each one." On each trial children were asked to tell the time that would be shown, and then the stimulus card was presented. Children were next asked to explain how they had figured out the answer, with prompts to encour-
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age them to expand their explanations. The experimenter transcribed their responses.

Transformation task.—Three analog and three digital stimuli were used: 4:30, 4:23, and 4:50 for one display type and 8:30, 8:23, and 8:50 for the other. The X:30 problems were chosen because they can be solved largely by applying the knowledge that half an hour added to a half hour time completes the hour. The other two problem types were presumed to have analog or digital advantages. The X:23 problems seemed easier for addition operations than minute hand operations, and addition may be more likely for digital problems. However, the X:50 problems might be difficult to solve by addition because the minute value changes when the hour is completed, but easier to solve by considering the movement of the minute hand. General instructions for the task were, “In this part I’m going to ask you questions about some times. Please tell me the answers and any overt behavior or verbalization. Next, children were asked follow-up questions as in the detection task.

Optional transformation task.—Two problems involving adding a half hour and two involving subtracting a half hour were presented, in that order. One problem of each pair was analog and one was digital; one was based on a 4:00 time, the other on an 8:00 time: for the addition pair, 4:40 and 8:40; for the subtraction pair, 4:20 and 8:20. These problems were similar to the X:30 problems of the main transformation task in their apparent amenability to solution by imagining minute hand movement. We were interested in seeing whether the digital problems would evoke image mediation or whether the two display types would lead to different processes. The optional transformation task allows a more direct comparison of the methods used on analog and digital problems than the main transformation tasks because children were asked to compare the approaches they took to analog and digital presentations of the same problem.

Before each stimulus was presented, subjects were instructed to “tell me as you go along whether you are thinking about a clock face with hands moving or thinking about numbers in your mind or doing it some other way.” The order of the italicized phrases varied randomly. For the addition pair, questions were of the same form as in the main transformation task. For the subtraction pair, subjects were told, “This clock says ——— [time given],” and asked what it had said 30 min ago. The experimenter recorded the answer and any verbalizations. Follow-up questions were used as in the main transformation task. After each pair of problems, children were asked, “One of these problems had a clock face and the other had numbers. Did you do these the same way?” This was followed by prompts, such as, “Can you tell me more?” and “Did you think about adding numbers for both, or a clock face and moving hands for both?”

RESULTS

Detection

Proportion correct.—The mean proportion correct for detection problems is shown in the top half of Table 1. The response “Don’t know” was scored as an error in this and subsequent analyses. For digital problems even first graders are able to read the display as a time, and performance is essentially perfect by second grade. Of the analog set, only the X:00 problems are about as accurate as the digital ones. The X:30 problems are mastered by second grade, but X:43 problems remain difficult through third grade and later.

Because of the high levels of accuracy (and thus limited variance) after first grade for two of the analog problems and all of the digital problems, an overall ANOVA was not appropriate. A separate repeated-measures ANOVA was performed for the first grade along with school, sex, and order (digital problems first or second) as between-subject factors, and analog versus digital and time (X:00, X:30, and X:43) as within-subject factors. Sex was significant alone, F(1,24) = 12.08, p < .02, and in the three-way interaction with analog versus digital and time, F(2,48) = 5.68, p < .01. These effects reflect the fact that boys were more accurate overall at this age and that their accuracy was more uniform across digital problems than girls'. Of greater interest are the clear findings that digital detection was superior to analog detection, F(1,24) = 43.24, p < .001, that time displayed was a significant source of variance, F(2,48) = 14.01, p < .001, and that this time effect was attributable to the analog, not digital condition, analog versus digital X time, F(2,48) = 20.27, p < .001. Two nonorthogonal
TABLE 1
MEAN PROPORTION CORRECT FOR EACH GRADE ON THE DETECTION AND TRANSFORMATION TASKS IN EXPERIMENT 1

<table>
<thead>
<tr>
<th>GRADE</th>
<th>ANALOG</th>
<th>DIGITAL</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>:00</td>
<td>:30</td>
</tr>
<tr>
<td>Detection:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>.72</td>
<td>.37</td>
</tr>
<tr>
<td>2</td>
<td>.97</td>
<td>.91</td>
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<td>3</td>
<td>.88</td>
<td>.97</td>
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<tr>
<td>4</td>
<td>1.00</td>
<td>.97</td>
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<tr>
<td>5</td>
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<td>Transformation:</td>
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<td></td>
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<tr>
<td>1</td>
<td>.16</td>
<td>.06</td>
</tr>
<tr>
<td>2</td>
<td>.59</td>
<td>.16</td>
</tr>
<tr>
<td>3</td>
<td>.72</td>
<td>.34</td>
</tr>
<tr>
<td>4</td>
<td>.97</td>
<td>.53</td>
</tr>
<tr>
<td>5</td>
<td>.91</td>
<td>.44</td>
</tr>
<tr>
<td>Mean</td>
<td>.67</td>
<td>.31</td>
</tr>
</tbody>
</table>

planned comparisons revealed significant differences between the analog X:00 and X:30 means, F(1,90) = 4.10, p < .05, and between the analog X:30 and X:43 means, F(1,90) = 3.99, p < .05.

A separate ANOVA tested grade differences in the analog X:43 problems alone. It revealed a highly significant grade effect, F(4,155) = 22.02, p < .001, and a highly significant linear grade trend, F(1,155) = 78.09, p < .001. The linear trend shows that accuracy improves continuously during this age range.

Reported methods.—A rater assigned the children's reports on their methods of solution to one of two categories for the digital set and four categories for the analog set. Interobserver agreements with random samples of 100 responses were 98% for the digital set and 72% for the analog set. The first rater's assignments were used in our analyses. The method categories are listed in Table 2, which also shows the proportion of correct and incorrect reports assigned to each category for each stimulus time. The digital category “direct reading” included describing or explaining the display or simply pointing out that one's answer was the time shown or that one could tell by looking at it. The analog category “direct reading” included stating that one just knew the answer, explaining some correct clock fact such as that 60 or 12 equals a whole hour or that 6 equals 30 min, or simply describing where the hands pointed. The category “appropriate multistep operation” included explaining a procedure for deriving the minute hand value, such as counting each number by 5s, often starting at 6, or counting hash marks from the 8. “Incorrect dynamic” included erroneous rules about the clock, such as using a minute hand rule to read the hour hand position.

For the digital detection problems, between 90% and 95% of children who gave correct answers reported that they read the display directly. An example is, “It just says 8:30.” The few children who made mistakes mostly reported some version of “by looking at it” or merely described the display.

Of children who were correct on the analog detection problems, about 80% reported some sort of direct reading method for the X:00 and X:30 problems, whereas the overwhelming majority reported a multistep operation for the X:43 problems. These methods were reported by fewer than a third of children who gave incorrect answers, though it is notable that many who were incorrect on the X:43 problems referred to appropriate operations. Most children who gave erroneous answers did not explain how they arrived at them or cited some incorrect rule.
Given the considerable consistency in the methods reported for arriving at correct answers, there was little room for age differences. Nevertheless, we performed Pearson $\chi^2$ tests of association between grade and reported methods for correct items on each of the three problem types for the analog and digital sets (left half of Table 2). These tests must be interpreted with caution because of the large proportion of cells with small expected frequencies. Only two of these tests, those for analog detection $X:00$ and $X:30$, reached conventional levels of significance, $\chi^2(12, N = 146) = 25.11, p < .02$, and $\chi^2(12, N = 132) = 27.96, p < .01$, respectively, and neither showed continuous age trends. In each case the dominant method in Table 2 was the dominant method at each age. Thus, it appears that the main age trends are from methods associated with incorrect answers to methods associated with correct answers, with little change in the distribution of methods among correct answers.

Transformation

Proportion correct.—The bottom half of Table 1 shows the accuracy results for the transformation task. For both the analog and digital sets, children’s transformation performance lagged well behind their detection performance (shown on the top half of Table 1). Both sets of problems showed nearly identical overall proportions correct, and for both sets the X:30 problems were the easiest. They were the only problems where half or more of the children were accurate before third or fourth grade. The X:23 problems remained difficult even for the oldest children, especially in the analog set. The only apparent analog-digital difference is that in the digital set X:23 and X:50 showed approximately equal proportions correct, but in the analog set the X:50 problems were easier.

A repeated-measures ANOVA was performed with school, grade, sex, and order (digital problems first or second) as between-subject factors, and analog versus digital and time (X:30, X:23, and X:50) as within-subject factors. Of the main effects, school, $F(1,120) = 7.72, p < .01$; grade, $F(4,120) = 14.32, p < .001$; sex, $F(1,120) = 12.77, p < .01$; order, $F(1,120) = 6.16, p < .02$; and time, $F(2,240) = 51.05, p < .001$, were significant, whereas analog versus digital was not. Schools A and B had means of .55 and .43, males were more accurate than females (.56 vs. .41), and children who received the digital set first were more accurate overall (.54 vs. .44). Grade changes and time differences are shown in the bottom half of Table 1.

Four two-way interactions were significant. Most interesting was the interaction between analog versus digital and time, $F(2,240) = 6.70, p < .01$. Because the overall means for analog and digital X:30 are essentially identical, this shows that, as expected, the analog and digital sets differ in the relative difficulty of the X:23 and X:50 problems. Time interacted with grade, $F(8,240) = 2.32, p < .03$, apparently because X:30 problems reach high levels of accuracy at earlier ages than X:23 and X:50 problems. The interaction between grade and analog versus digital, $F(4,120) = 2.62, p < .04$, probably resulted from the slightly more accurate analog performance at grades 2 and 4, as contrasted with somewhat more accurate responses on the digital set at grade 5. The interaction between analog versus digital and school, $F(1,120) = 5.41, p < .03$, reflected a small crossover in

### Table 2

<table>
<thead>
<tr>
<th>Reported Method</th>
<th>Answer Correct</th>
<th>Answer Incorrect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X:00</td>
<td>X:30</td>
</tr>
<tr>
<td>Analog detection:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct reading</td>
<td>.92</td>
<td>.79</td>
</tr>
<tr>
<td>Appropriate multistep</td>
<td>.03</td>
<td>.17</td>
</tr>
<tr>
<td>operation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incorrect dynamic</td>
<td>.02</td>
<td>.02</td>
</tr>
<tr>
<td>Don’t know or other</td>
<td>.03</td>
<td>.02</td>
</tr>
<tr>
<td>Digital detection:</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>.90</td>
<td>.95</td>
</tr>
<tr>
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<td>.10</td>
<td>.05</td>
</tr>
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TABLE 3

PROPORTION OF REPORTED METHODS ASSIGNED TO EACH CATEGORY IN THE ANALOG AND DIGITAL TRANSFORMATION TASKS IN EXPERIMENT 1

<table>
<thead>
<tr>
<th>REPORTED METHOD</th>
<th>ANSWER CORRECT</th>
<th>ANSWER INCORRECT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X:30</td>
<td>X:23</td>
</tr>
<tr>
<td>Analog transformation:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Just knew</td>
<td>.17</td>
<td>.00</td>
</tr>
<tr>
<td>Count by 5s or 10s</td>
<td>.16</td>
<td>.31</td>
</tr>
<tr>
<td>Addition</td>
<td>.22</td>
<td>.51</td>
</tr>
<tr>
<td>Completes the hour</td>
<td>.32</td>
<td>.00</td>
</tr>
<tr>
<td>Movement of minute hand</td>
<td></td>
<td>.10</td>
</tr>
<tr>
<td>No answer or other</td>
<td>.03</td>
<td>.14</td>
</tr>
<tr>
<td>Digital transformation:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Just knew</td>
<td>.14</td>
<td>.00</td>
</tr>
<tr>
<td>Count by 5s or 10s</td>
<td>.09</td>
<td>.17</td>
</tr>
<tr>
<td>Addition</td>
<td>.35</td>
<td>.70</td>
</tr>
<tr>
<td>Completes the hour</td>
<td>.22</td>
<td>.00</td>
</tr>
<tr>
<td>Analog reference</td>
<td>.12</td>
<td>.03</td>
</tr>
<tr>
<td>No answer or other</td>
<td>.08</td>
<td>.09</td>
</tr>
</tbody>
</table>

the relative difficulty of the analog and digital sets for the two schools. A three-way interaction between order, analog versus digital, and time was also significant, $F(2,240) = 3.11, p < .05$.

Reported methods.—Method reports for the transformation problems were assigned to one of six categories for each of the analog and digital sets (see Table 3). Interobserver agreements with random samples of 100 responses were 79% for the analog set and 82% for the digital set. Most of the categories are self-explanatory. For the category “count by 5s or 10s,” we presumed that children were covertly counting 5-min marks on the clock face in the analog condition and counting by decades in the digital condition. Overt behaviors like pointing and lip movement were very rare, thus preventing us from confirming these interpretations. The category “analog reference” involved referring to a clock face in explaining one’s method.

Reports accompanying correct answers are considered first. Similar methods were reported on the analog and digital sets for the X:30 and X:23 problems. Methods suggesting direct retrieval were common on both sets on the X:30 problems. These include simply reporting that a half and a half make a whole, or complete hour, or that one just knew the answer. Addition was also a common reported method on the X:30 problems. Counting by 5s or 10s and addition were the most common methods for both the analog and digital X:23 problems, though addition was favored somewhat more strongly in the digital condition. This difference was especially pronounced on X:50 problems, with the majority of reports for the analog set indicating counting by 5s or 10s and the majority of the reports for the digital set indicating addition.

Only a minority of reports accompanying incorrect answers could be classified in these categories. However, it is notable that many children whose answers were incorrect on the analog transformation X:23 and X:50 problems reported relevant operations, counting by 5s or 10s.

As for the detection tasks, we computed Pearson $\chi^2$ tests of age differences in the methods associated with correct answers. The distribution of methods was significantly associated with grade for the analog X:30 and X:50 problems, $\chi^2(20, N = 107) = 41.83, p < .01$, and $\chi^2(16, N = 78) = 27.02, p < .05$, respectively. For the X:30 problems, there was a developmental decrease in counting by 5s and 10s and increases in “addition,” “completes the hour,” and “movement of minute hand.” This may reflect a trend away from multistep procedures and toward more direct solutions to half-hour problems. There were no clear age trends for the X:50 problems, though there was some tendency for counting by 5s and 10s to decrease with age and “addition” and “movement of minute hand” to increase with age.

Optional Transformation

Two procedures were used to analyze the optional transformation data. First, a re-
peated-measures ANOVA of proportion correct included the factors grade, sex, analog versus digital, and plus versus minus transformation. Only the grade effect was significant, F(4,43) = 5.57, p < .01. The absence of a significant analog versus digital effect was consistent with the results of the main transformation task, though the absence of a sex effect was not. Within the limits of inference from a null finding, and bearing in mind the confounding between plus versus minus and task order, it appears that subtracting one half hour (mean proportion correct = .65) is no more difficult than adding one half hour (mean = .64).

The second analysis was intended to determine whether we could differentiate the approaches taken on the analog and digital tasks. Judges were instructed to read all of the available information for each problem (including answers, the methods reported and answers to the follow-up questions), and then to assign the problem to one of 12 method categories. Three of these categories were for primarily numerical operations (such as addition, subtraction, or counting), and three involved operations on a clock face or image of a clock face (e.g., overt or covert stepwise movement, or direct 180° movement of the minute hand). The remaining six categories were: a combination of numerical and clock face operations; a category in which the rater could not distinguish which of the two was used; and categories for generalizing the answer from a previous problem, reporting a rule, unclassifiable responses, and insufficient material. One of the first two raters appeared to overuse the “combination” category, so a third rater was added. Final classifications included only responses where two or three of the three raters agreed on the assignment to one of the 12 categories. With 12 categories the expected proportion of agreement for two or three out of the three raters is .24. The actual rates of agreement for the four problems ranged from .90 to .92.

Table 4 presents the results for collapsed numerical and collapsed clock face categories and the combination category. Excluded are responses that failed to meet the interobserver agreement criterion or fall in the other categories. For the digital problems, primarily numerical methods accounted for approximately three quarters of the responses. For the analog problems, numerical methods were also common, but about half fell in the combination category. The clock face category accounted for about one tenth of the responses on each problem. There was no evidence of age differences for any of the four problems: Chi square analyses of method \times grade were not significant.

It may be that the presence of a digital display (or the absence of a clock face) on the digital problems produces a bias to use addition, subtraction, or unit counting, though about one-quarter of the responses suggested analog imagery. When a clock face is provided along with the time name on the analog problems, imagined operations on the clock face predominate. These operations occurred mainly in the category combining clock face and numerical methods, probably because children usually counted the 5-min marks around the clock face. When children reported counting, it was often difficult to determine whether they meant a purely numerical method, such as counting by 10s, or whether they were sequentially attending to marks on the clock face. Thus, the numerical category probably includes some children who at least partially used clock face operations, whereas the combination category probably includes more complete reports of counting around the clock face.

**DISCUSSION**

The pattern of results for the two display types clearly supported the distinction between reading skills and operation skills. Digital time reading was very accurate by first
grade and virtually perfect by second grade, whereas analog performance varied greatly according to the display time. Whole-hour times were accurately read by first grade and half-hour times by second grade, but the X:43 problems did not reach comparable levels until the third grade, and they remained difficult for at least some children through the fifth grade. Mastery of transformation tasks lagged behind detection by several years: not until the fourth or fifth grades were children accurate on most of the problems. However, in contrast to detection, there was no overall difference in the difficulty of analog and digital problems. In general, the problems that we expected would involve multistep mental sequences—analogue X:43 detection problems and analog and digital X:23 and X:50 transformation problems—were relatively late acquisitions. By contrast, problems presumed to involve substantial retrieval components—analogue X:00 and X:30 detection problems and all digital detection problems—were solved at relatively early ages. Analog and digital X:30 transformation problems appeared to fall between the two sets in difficulty, perhaps reflecting a developmental shift from procedural sequences alone to a greater reliance on the principle that 2 half hours equal a whole hour.

Reported methods also supported our analysis of the processes involved in detection and transformation. Most children reported reading the times directly for digital detection in general and analog detection of whole-hour problems. These retrieval-like processes (see also Siegler & McGilly, in press) cannot be precisely characterized on the basis of our findings or previous ones, but they are clearly distinguishable from the procedural approaches taken on X:43 analog detection and most transformation problems. The methods reported for the analog detection X:43 problems showed the use of the 5-min-multiple and 1-min-increment procedures that children are commonly taught. Procedural approaches were also evident in the analog and digital transformation tasks. Counting by 5s or 10s, either numerically or around the clock perimeter, and addition were frequently reported.

It is interesting that children often used different procedures for the analog and digital transformation tasks, even though the starting times were always given aloud. The X:50 problems were somewhat easier than the X:23 problems in the analog but not digital conditions. This suggests that the presence of the clock face allows children to exploit the 180° spatial relation between pairs of times, at least when they are 5-min multiples. The optional transformation task also showed that children often performed clock face operations when an analog stimulus was present, whereas digital stimuli evoked mainly numerical approaches.

**Experiment 2**

In the second experiment, we repeated the detection and transformation tasks but did not ask the children to describe their methods. This change allowed us to see whether the results of Experiment 1 were likely to have been distorted by the thinking-aloud instructions or the follow-up method probes. Second, we added a number of tasks concerning the meaning of clock times. Two of these asked children to specify activities that typically take place at a particular clock time or to report the time at which particular activities usually occur. These tasks could be solved if children simply possess associative pairs between time names and activities, so we predicted that they would be early achievements. We also asked children to order sets of four cards, each of which represented a particular time. In one condition the cards were pictures of daily activities, in another they were clock times, and in a third they contained two activity pictures and two clock times. These tasks assess children’s knowledge of when particular times occur relative to other times. We were interested in determining whether clock times were incorporated in children’s first representations of the structure of daily activities or were a later addition.

**METHOD**

**Subjects**

Sixteen children from each of grades 1–5 participated in the study. They came from a small, socioeconomically mixed college town in rural Ohio. The sample was evenly divided by sex at each grade. Mean ages for the five grades are 7.1, 8.6, 9.1, 10.3, and 11.2.

**Procedure**

Each child was given four tasks, in the order listed below, in a single session of less than 30 min. The detection and transformation tasks were administered first according to the same ordering scheme as in Experiment 1 and followed identical procedures, except that children were not asked to think aloud or to explain their methods.

**Order task.**—Children were asked to order four sets of four cards each. One set con-
tained depictions of a child having breakfast, children arriving at school, a child eating lunch, and a child arriving home from school. The second set consisted of digital cards similar to those used in the detection and transformation tasks. They showed the times 9:00, 11:00, 1:00, and 3:00. The last two sets each contained two activity cards and two digital cards. One used the cards breakfast, 9:00, lunch, and 3:00. The other used arriving at school, 11:00, 1:00, and arriving home. All cards were approximately 6.5 x 8.0 cm. Half of the children received the activity set first and the digital set second; the other half received the reverse order. The mixed sets were presented third and fourth in counterbalanced order.

At the start of the activity and digital tasks, children were shown the four cards in a constant random order and told, “These are all times/things that happen after you get up in the morning and before dinner. They happen between waking and dinner time.” Next, children learned the card meanings until they met the criterion of one perfect identification of all four. Then the experimenter said, “I want you to put them in order. That means I want you to put them in a line, with the first thing that happens here, and the next thing that happens here [etc.].” Prior to the mixed sets, children were instructed, “The next bunch have some times and some things that happen. All of them are still between waking and dinner time. I want you to put them in order.” The experimenter recorded the orders produced for each set.

Mapping task.—For each of five times (10:00, 2:00, 6:00, 8:00, and 4:00, in that constant random order), children were asked, “What do you usually do at [time]?” Unless they specified A.M./P.M. or a part of the day (e.g., morning), they were asked, “Which [time] is that?” In the second part of the task, children were asked, “At what time do you ______?” for each of five activities in the following constant random order: eat dinner, go to school, go to bed, get up in the morning, and eat lunch.

RESULTS

Detection

Proportion correct.—The top half of Table 5 shows the mean proportion correct for the detection problems. The levels and patterns of accuracy are similar to those shown in Table 1 (Experiment 1), except for the somewhat greater grade-to-grade fluctuations one might expect in the present smaller sample. An ANOVA was performed on the first graders’ data, as for Experiment 1, except that school was not a factor. Again, analog versus

<table>
<thead>
<tr>
<th>GRADE</th>
<th>ANALOG</th>
<th>DIGITAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>.00</td>
<td>.30</td>
</tr>
<tr>
<td>Detection:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>.94</td>
<td>.75</td>
</tr>
<tr>
<td>2</td>
<td>.88</td>
<td>.38</td>
</tr>
<tr>
<td>3</td>
<td>.94</td>
<td>1.00</td>
</tr>
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<td>4</td>
<td>.94</td>
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<td>5</td>
<td>.87</td>
<td>.94</td>
</tr>
<tr>
<td>Mean</td>
<td>.91</td>
<td>.79</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>ANALOG</th>
<th>DIGITAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>:30</td>
<td>:23</td>
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<tr>
<td>Transformation:</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>.19</td>
</tr>
<tr>
<td>2</td>
<td>.37</td>
</tr>
<tr>
<td>3</td>
<td>.94</td>
</tr>
<tr>
<td>4</td>
<td>1.00</td>
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<tr>
<td>5</td>
<td>.88</td>
</tr>
<tr>
<td>Mean</td>
<td>.67</td>
</tr>
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</table>
**Transformation**

Proportion correct.—The bottom half of Table 5 shows the mean proportions correct in the transformation task. Again, the levels and patterns are consistent with those seen in Experiment 1 (Table 1). The ANOVA replicated the grade effect, \( F(4,60) = 16.22, p < .001 \), but sex, order, and time were not significant, as they had been in Experiment 1. It is important to note that analog versus digital was not significant in either study, showing that digital clocks are easier for detection but not for transformation.

Two of the original three two-way interactions were significant: time \( \times \) grade, \( F(8,120) = 2.10, p < .05 \); and grade \( \times \) analog versus digital, \( F(4,60) = 4.07, p < .01 \). Although the analog versus digital \( \times \) time interaction was not replicated (\( p < .07 \)), we tested its most interesting component, the analog versus digital difference in X:23 versus X:50 problems, and this comparison was significant, \( F(1,75) = 5.43, p < .03 \). This confirms the finding that X:50 problems are easier than X:23 problems in the analog but not digital conditions. No other effects were significant.

**Order Task**

Table 6 shows mean Spearman rank-order correlation coefficient between the orders that children produced on the order tasks and the correct orders. Scores on the two integrated tasks were averaged because they revealed similar age trends. These results indicate that children know the order of familiar daily events at least by first grade, whereas digital clock times cannot be interrelated by most children until second grade. The integrated sets of activities and times were ordered at above chance levels by first grade but continued to increase in accuracy until third grade.

**Mapping Task**

Responses to the mapping task were scored according to a schedule of times we considered plausible (e.g., get up: 6:00-9:00 A.M.; dinner: 4:30-7:30 P.M.). For a response to be scored correct, children did not have to specify A.M./P.M. or a part of the day. However, if they did so in the activities-to-times subtask the combination needed to be correct. Inter-

---

**Table 6**

**Mean Spearman Rank-Order Correlation Coefficient for Each Grade on the Order Tasks of Experiment 2**

<table>
<thead>
<tr>
<th>GRADE</th>
<th>Activity</th>
<th>Digital</th>
<th>Integrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00 *</td>
<td>.96*</td>
<td>.40</td>
<td>.44*</td>
</tr>
<tr>
<td>1.00 *</td>
<td>.74*</td>
<td>.61*</td>
<td></td>
</tr>
<tr>
<td>1.00 *</td>
<td>.74*</td>
<td>.92*</td>
<td></td>
</tr>
<tr>
<td>1.00 *</td>
<td>.71*</td>
<td>.91*</td>
<td></td>
</tr>
<tr>
<td>1.00 *</td>
<td>.55*</td>
<td>.91*</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>.98</td>
<td>.47</td>
<td>.76</td>
</tr>
</tbody>
</table>

* \( p < .001 \) by one-tailed \( t \) test that \( r = 0 \).

Eighty percent of the first graders’ errors on the digital task involved placing the cards in numerical order (1, 3, 9, 11), but this response accounted for fewer than half of the errors by older children. Because the numerical order is correct for some intervals (half days beginning at noon or midnight) and because the acceptable interval was specified in terms of activities (waking and dinner) it could be argued that the first graders’ deficit was in translating the boundary activities into clock times and not in constructing a correct order for morning and afternoon. However, as the mapping task reveals, half or more of even first graders can give reasonable clock times for waking and dinner, so this is unlikely to account for the very low levels of accuracy in the first-grade group.

A repeated-measures ANOVA compared the three order scores as a function of grade. Task, \( F(2,150) = 52.16, p < .001 \), grade, \( F(4,75) = 15.14, p < .001 \), and their interaction, \( F(8,150) = 10.41, p < .001 \), were all significant. A planned comparison showed the activity set to be significantly more accurate than the other two sets, \( F(1,150) = 29.20, p < .01 \), and the significant interaction supports the description that the activity set did not show the developmental increases of the other two.
TABLE 7
MEAN PROPORTION CORRECT FOR EACH GRADE ON THE MAPPING TASKS IN EXPERIMENT 2

<table>
<thead>
<tr>
<th>GRADING</th>
<th>STIMULUS TIME</th>
<th>2:00</th>
<th>4:00</th>
<th>6:00</th>
<th>8:00</th>
<th>10:00</th>
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<tbody>
<tr>
<td>Grade 1</td>
<td>Time-to-activities task:</td>
<td>.19</td>
<td>.19</td>
<td>.37</td>
<td>.62</td>
<td>.75**</td>
</tr>
<tr>
<td>Grade 2</td>
<td>.83</td>
<td>.75**</td>
<td>.69*</td>
<td>.81**</td>
<td>.69*</td>
<td></td>
</tr>
<tr>
<td>Grade 3</td>
<td>.81**</td>
<td>.75**</td>
<td>.81**</td>
<td>.87**</td>
<td>.94**</td>
<td></td>
</tr>
<tr>
<td>Grade 4</td>
<td>1.00**</td>
<td>.75**</td>
<td>.88**</td>
<td>.81**</td>
<td>.88**</td>
<td></td>
</tr>
<tr>
<td>Grade 5</td>
<td>1.00**</td>
<td>.75**</td>
<td>.75**</td>
<td>1.00**</td>
<td>1.00**</td>
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<tr>
<td>Mean</td>
<td>.73</td>
<td>.64</td>
<td>.70</td>
<td>.82</td>
<td>.85</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>STIMULUS ACTIVITY</th>
<th>Dinner</th>
<th>Arrive at School</th>
<th>Go to Bed</th>
<th>Get Up</th>
<th>Lunch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activities-to-times task:</td>
<td></td>
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<td></td>
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<tr>
<td>Grade 1</td>
<td>.50**</td>
<td>.63**</td>
<td>.87**</td>
<td>.56**</td>
<td>.37*</td>
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<tr>
<td>Grade 2</td>
<td>.69**</td>
<td>.81**</td>
<td>.94**</td>
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<td>1.00**</td>
<td>.94**</td>
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<td>1.00**</td>
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<tr>
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<td>1.00**</td>
<td>1.00**</td>
<td>1.00**</td>
<td>.94**</td>
</tr>
<tr>
<td>Mean</td>
<td>.76</td>
<td>.89</td>
<td>.93</td>
<td>.88</td>
<td>.79</td>
</tr>
</tbody>
</table>

NOTE.—Entries are subject to rounding error.
* p < .06 by binomial test against estimated chance level for the task.
** p < .01 by binomial test against estimated chance level for the task.

observer agreement was .95 for the subtask in which the stimuli were times and .97 for the subtask in which activities were presented. The first rater's assignments were used.

Table 7 shows the results for the two subtasks. The significance levels refer to one-tailed binomial tests using estimates of chance levels of performance for the null hypothesis. These estimates were obtained by scoring as correct or incorrect random combinations of mismatched responses to problems for half of the children (e.g., an answer to the dinner question was scored as if it has been given to the lunch question). Chance level estimates were .41 correct for the times-to-activities subtask and .14 for the activities-to-times subtask. Even by first grade, most children knew the times of several activities and could name likely activities for some, but not all, times. Second graders had more complete knowledge of time-activity correspondences. A separate tabulation of the number of children correctly specifying A.M./P.M. either spontaneously or in response to the follow-up question in the times-to-activities subtask (interobserver agreement: .94) showed that a mean of half or more children were correct by second grade.

DISCUSSION

Experiment 2 replicated the main findings for accuracy in the first experiment. Again, except for analog times to the minute, clock reading occurred well before children could perform operations, and the digital advantage for reading did not extend to the transformation task. We also repeated the finding that relative problem difficulty differs for analog and digital transformation problems. Children seemed to take advantage of spatial solutions to the analog X:50 problems, rendering them easier than adding 30 min to the non-5-min multiple times.

Among the new findings, the youngest group could link many times and activities. This ability precedes accurate ordering of clock times or integrated sets of activities and clock times, probably because individual associative pairs are acquired before representations of order that include clock times. But not all representations of order are late acquisitions: consistent with previous studies (Friedman, 1977; Muto, 1982), first graders were very accurate in ordering cards representing daily activities. The delay between ordering daily activities and ordering clock times
show that hours are not the first code for representing daily order.

**General Discussion**

The gradual acquisition demonstrated in this study shows the importance of distinguishing different components of clock knowledge and of describing the multiple representations and processes that underlie it. Children apparently bring to the task of clock learning knowledge of a number of associations between times and activities as well as representations of when daily activities occur relative to one another. By first grade they apply number reading skills to digital displays and to certain landmark analog configurations. In the next year or two, children develop representations of the relative times of occurrence of hours of the day. By third grade most children have acquired considerable skill in reading the large number of analog times to the minute, though these problems remain difficult at least through fifth grade. The ability to operate on clock times appears relatively late for both analog and digital displays, with some success by third grade but slow improvement in the following years.

We suggested earlier that procedural sequences, retrieval, associations, and order representations may all play a role in clock knowledge, and we are now in a position to consider these claims. The clearest evidence is for the role of procedural sequences in analog detection and both analog and digital transformations. The reported methods paint a picture that is consistent with that of Case et al.'s (1986) analysis of adults' and Siegler and McGilly's (in press) analysis of children's analog detection. Not only is the relative difficulty of different problems quite similar in the three studies (e.g., whole hours are easier than 5-min multiples, which are easier than times to the minute), but there are striking similarities in strategy reports. For example, all three studies found strategies involving incrementing the minute value by 5-min multiples.

These findings support the role of procedural processing in analog detection. Case et al.'s (1986) and Siegler and McGilly's (in press) results show a number of effects that appear to be the same for children and adults, such as a right-sector advantage for certain times and slower responses for minute readings that are farther from 5-min multiples. It is also worth noting that slow responding on times to the minute, both in relative and absolute terms, is preserved into adulthood: Siegler and McGilly's second and third graders took about twice as long to solve times to the minute as whole hour times, our fifth graders (in data not reported here) took more than three times as long, and Case et al.'s adult subjects took about twice as long (still about 3 sec). These results suggest that the processes underlying analog detection remain fundamentally unchanged after childhood.

The present study also showed the likely involvement of procedural processing in the transformation tasks because reported methods seemed to reflect multistep operations. We also found evidence that the operations often differed for analog and digital displays, even though the starting times were given aloud for both. Digital displays seemed to evoke mainly numerical approaches, such as addition or incrementing by decades, though analog mediation was occasionally reported. Analog problems evoked a mixture of approaches, including many that capitalized on the spatial properties of the display.

There is less evidence concerning the role of retrieval and associations in clock knowledge. The most direct evidence for retrieval-like processes came from the frequent reports of directly knowing the answer on these problems. Siegler and McGilly (in press) reported similar findings for their whole-hour (analog) problems. They believe that performance on certain problems is based on accessing associations between particular configurations and time names. However, neither their methods nor ours are adequate to precisely characterize the underlying processes.

Indirect evidence for the involvement of associative processes in time knowledge comes from the finding that clock times can be linked to activities before they can be ordered themselves. This seems to indicate that some type of representation containing relatively little relational information is involved in the early knowledge.

The case for qualitatively different representations of order is purely circumstantial. Preschool children possess reliable knowledge of the order of daily activities (Friedman, 1977; Friedman & Bronos, 1988; Muto, 1982; Nelson, 1986), 10-year-olds to adolescents represent week and month order (Friedman, 1986), and in between we find that second and third graders learn to order the hours of the day, to relate them to landmark activities, and to distinguish A.M. times from P.M.
times. It seems likely that clock times, like daily activities, months, and days of the week, can be "localized" through processes more direct than procedural sequences and on the basis of representations richer than associative pairs, but such a conclusion must await further research.

In this study we used age differences to distinguish between different components of clock knowledge. But one can also ask what developmental factors are responsible for the gradual acquisition of this knowledge. We assumed that associative links and retrieval-based processes would be acquired at relatively early ages, procedural sequences at relatively late ages, and order representations at ages determined by the number of elements represented and the number of exposures to the sequence. Two other accounts of the development of clock knowledge are also compatible with many of our findings.

Case et al. (1986) believe that under conditions of spontaneous acquisition, children's understanding of the clock system will be limited by their status in a series of age-related stages, each characterized by the number of dimensions or variables that can be evaluated in a problem. Aside from the difficulty of determining objectively what is a "dimension" in some new domain, the model is generally successful in predicting the order in which children can extract information about the hour hand, hour hand and 5-min multiples, and these two plus 1-min increments. As we saw earlier, the developmental sequence of whole hour times, 5-min multiples, and times to the minute has been amply demonstrated. Their model is even stronger in that it predicts not only the sequence but the ages at which different levels of proficiency are achieved. The model may be of somewhat limited value for the present results because it is not explicit about when associations between times and activities should be present. It could be argued, though, that these are compatible with "polar dimensional (global) thought," in which case the mapping performance of our first graders would support their theory. Perhaps most troublesome is the difficulty of knowing at what age children should be able to order daily activities, clock times, days of the week, or months. It is not obvious how Case et al.'s model analyzes what we have called order representations, nor how it would explain the fact that children appear to learn to order elements of these structures at ages ranging from about 4 years for daily activities to 10 years for days of the week and months.

Siegler and McGilly (in press) applied the strategy-choice model (Siegler & Shrager, 1984) to analog clock reading skill. They believe that children read clocks by using a mixture of retrieval and backup strategies. Although their study does not test age differences, the general model predicts that older children will rely more on retrieval because through practice they will develop more peaked associations to particular problems (see Siegler & Shrager, 1984). However, the substantial differences between adults' response times for whole hour times and times to the minute (Case et al., 1986) make it unlikely that retrieval replaces procedural approaches on all problems. More likely, given the large number of clock times to the minute, retrieval merely streamlines one or more constituents of what for many problems remains a partially procedural process. This would be analogous to the routinization of sum retrieval in multiplication addition but adults' continued reliance on procedural sequences. In addition, as for Case et al.'s model, it is unclear how well the strategy choice/distribution of associations model can explain the development of the ability to relate different times to one another.

References


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