

Spilling thoughts: Configuring attentional resources in infants' goal-directed actions¹

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Abstract

The focus and organization of attention in perception-action coupling is systematically examined in two studies involving 9½ and 10½-month-old infants engaged in learning goal-directed behaviors. Experiment 1 (*discrimination study*) observed the influence of an attentionally demanding motor task on learning and cognition, while Experiment 2 (*means-ends study*) observed the influence of an attentionally demanding goal on motor planning and reaching performance. Taken together the results of these two experiments revealed that when mental processing resources were directed to thinking about movement, discrimination performance became compromised; conversely, when processing resources were directed to thinking about the goal-state, the motor planning and execution became compromised. These results suggest a “spilling forward” of thoughts onto actions and goal-states and thus an attention-driven *cognition/action trade-off* for infants' goal-directed actions. Findings highlight the ultimate importance of emerging motor skills on cognition and are contextualized within the on-going dialogues and developmental debates surrounding perceptual-motor skill development and problem-solving strategies during the first year. © 2000 Elsevier Science Inc. All rights reserved.

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1. Introduction

In exploring the origins of intelligence in children, Jean Piaget (1952) introduced into our scientific lexicon his often cited concept of *sensorimotor* development. As a *portemanteau* word, *sensorimotor* draws immediate attention to the coupling nature of perception and action, a coupling on which hinges a great deal of theoretical and experimental debate, including the scholarly examinations in this special issue of *IBAD*. In a recent address, for example, Esther Thelen reminded international infancy scholars of the long line of cross-disciplinary thinkers including James, Merleau-Ponty, and Gibson who have theorized the perception-action linkage in the pursuit of the embodied mind; she notes: “. . . cognition depends on the kinds of experiences that come from having a body with particular perceptual and motor capabilities that are inseparably linked and that together form the matrix within which reasoning, memory, emotion, language, and all other aspects of mental life are embedded” (Thelen, 2000, p. 5). Thus the challenge to explicate the synergistic contributions of perception and action for infants’ goal-directed behavior and ultimately for mapping the architecture of early intelligence remains a galvanizing goal for infancy researchers.

From Gibson’s (1979) classic contributions and cogent observations of the perception-action cycle we know that the two systems have evolved in tandem to maximize our interactions with the environment; moreover, we now know that the flow of information (e.g., from vision to action) can occur with limited conscious effort and that attention, action, and vision are highly integrated (see Humphreys et al., 1999). With the efficient evolution of perception-action systems comes the opportunity for voluntarily acting on a plethora of choices, or affordances (Gibson, 1982), presented within the environment. For the infant to successfully exploit a perceptual-action coupling and achieve a desired goal, perceptual and motoric coordination is required at several levels including the biodynamic while also deploying the necessary mental focusing energies to attend to and oversee the goal acquisition. It is this recruitment and organization of attentional effort which is most associated with how adults select the perceptual input from which to chart a possible course of action. Compelling evidence from adult studies (see Tipper et al., 1999) suggests a very important relationship between attention and action such that actions are represented in an action-centered space at the cellular level of brain organization. Additionally, Rizzolatti, Riggio, Dascola and Umiltà (1987), in arguing for a premotor theory of attention, suggest a further cortical interconnection between action and attention such that a motor program for acting on an external reaching target or space can be attentionally monitored and represented.

Given the developmental relevance of the perceptual-action coupling and the fact that the infant spends a great deal of its first year engaged in extensive acts such as reaching, crawling, walking, social-mediated imitation and choice discrimination, the following questions emerge and guide the current study: *How does attention mediate, control, or organize infants’ goal-directed acts? How is the perception-action coupling influenced when the under- or overlying role of attention is considered? How might the role of attention serve to enhance our understanding of infants’ problem-solving strategies?*

The focal intent of this research is thus to engage the larger discourse surrounding the perception-action coupling in infancy by exploring the attentional organization and “make-up” of this coupling during goal-directed acts—the acts which are central for the infant’s

intellectual advancement and for highlighting the embodied nature of cognition. The role of attention has been crucially implicated in our understanding of a wide range of important developmental phenomena. For example, attention has been contextualized in the following areas: reflex modification and saccadic eye movements (Richards, 1998; Richards & Holley, 1999); visual development and categorization (e.g., Johnson & Aslin, 1995; Quinn & Eimas, 1998); intermodal and cross-modal development (e.g., Bahrick & Pickens, 1994); object exploration and knowledge (e.g., Ruff, 1996; Baillargeon, 1995); organization of memory (Adler et al., 1998); means-ends and problem-solving development (e.g., McCarty et al., 1999; Willatts, 1999); self knowledge (e.g., Rochat, 1995); continuity of intelligence (e.g., Bornstein & Sigman, 1986); and in social referencing and joint-attention (Moore & Corkum, 1994).

The role of attention has indeed been discussed extensively in these various accounts of development, but has typically played a secondary role; that is, attention is incorporated as a rate-limiting factor important for explaining positive, negative, or null findings. To our knowledge, the systematic manipulation of attentional focus and resource allocation in the context of the perception-action coupling represents a largely unexplored line of experimental inquiry in the developmental literature and stands to further expound the complex interplay among perceiving, thinking, and acting. By studying the *configuration of attention* within the perception-action dynamic, three central nodes of research emerge as important grounding for the current study: *studies of prehension*; *studies of goal-based problem solving*; and *studies of object search*, especially the *A-not-B (A \bar{B})* tasks.

A great deal of our advanced knowledge about the perception-action coupling in infancy comes from a rich array of studies that have explored the structure and organization of infant prehension and object retrieval tasks. From the onset of reaching around 4½ months infants exhibit remarkable skill at coordinating the visual input with the neuromotor demands of a young movement system (e.g., Berthier, 1996; Out et al., 1997; McCarty & Ashmead, 1999; Thelen et al., 1996; von Hofsten, 1979, 1991). Collectively, these studies have mathematically modeled and demonstrated that infants can control biomechanical factors, self-generated movement perturbations, demands of object visibility, and the varying demands of object properties and task dynamics; most importantly for this study, they have eloquently demonstrated how the infant's task is one of balancing competing forces that act both exogenously and endogenously in what appears like a simple retrieval of a target object.

In this context, reaching accuracy, perceptual-motor control, and kinematical expression may also reveal aspects of the infants' modulation and control of attention. For example, to what extent does a non smooth reaching trajectory or grasping profile reflect attentional constraints related either to the perception-action execution demands or to the task constraints? While it is well established that both adults (e.g., Martenuik et al., 1990) and infants (e.g., von Hofsten & Rönnqvist, 1988) take longer to complete reaching tasks when they have to attend to increased end-point accuracy demands, the issue here is rather one about the nature and organization of motor planning and control while undergoing *concurrent* attentional processing demands of learning a new goal-directed task.

Similarly, recent investigations on how infants and children develop efficient strategies and planful executions of goal-based problems provide a valuable context from which to

study the role of attention in the perception-action cycle. Studies by Willatts (1999), McCarty et al. (1999), and Bauer, Schwade, Wewerka and Delaney (1999) report a series of impressive findings from infants 6 to 24-months-of age. These findings demonstrate the critical shift from transitional to intentional-means behavior, multiple strategy development, for everyday prehension tasks, and the generation of smart solutions to novel problems. Again, the present study engages this line of research in that problem-solving skill must be regulated, in part, within an attentional frame of reference. To what extent does the infant's intentions (e.g., in pulling a cloth to get a toy or grasping a spoon to consume food) compete with the planning and executing of the task, as both simultaneously draw on limited attentional resources?

The final intersecting context concerns the perplexing $A\bar{B}$ error originally documented by Piaget (1954). Critical studies by Bell and Adams (1999), Diamond (1990), Hofstadter and Reznick (1996), Munakata, McClelland, Johnson and Siegler (1997), and Smith, Thelen, Titzer and McLin (1999) have provided a substantial debate regarding the sources of the error: brain circuitry associated with ocular and motoric movements; memory allocation; motor perseveration; knowledge representation; and differential task dynamics. How might the role of resource allocation of the visual-motor demands in the $A\bar{B}$ task contribute to this on-going dialogue?

What emerges from these contextual research nodes is the impetus for a study that systematically tests the focus of attention in infants' goal-directed actions. Specifically, we wish to experimentally explore how "motor load" and "cognitive load" are implicated in the nature of perception-action couplings. Thus, in Experiment 1, working from the limited resource model of attention (Kahneman, 1973; Fagot & Phashler, 1992; Hasher & Zacks, 1979; Navon, 1984; Treisman, 1986) we tested the hypothesis that the cognitive goal to which a motor response is prerequisite may become compromised if the planning and execution of the motor act itself requires substantial attention. Our working position on attention is thus derived from the basic notion that the infant has a limited pool of processing resources to draw from such that focusing mental energies on one task aspect may extract energies otherwise available for another critical task aspect.

In this study, 9½-month-olds were required to solve a classic-style two-choice S+/S-discrimination problem, analogous to an adult dual-task study, in that the infant must pay attention to two events simultaneously: the reaching action and the discrimination choice. In order to isolate the attentional effects of motor planning and execution on the discrimination learning, the *motor demands were manipulated* while the cognitive demands were held constant. It was hypothesized that performance on discrimination learning would be reduced when the motor planning and execution demands were heightened.

2. Experiment 1

2.1. Method

2.1.1. Participants

Fifty-five 9½-month-old infants (29 females, 26 males) each born within 2 weeks of the calculated due date served as the research participants. By this age, prehension skills are well

established and kinematically efficient; moreover, infants are motivated to enact repeated trials as is required to capture a learning function. All infants were recruited from the vital birth statistics from local towns in a greater metropolitan area; respondents to our recruitment materials are predominantly white, middle-class, two-parent families. All infants participated with a parent's informed, voluntary consent and were given a small gift for their participation.

2.1.2. Apparatus and motor task conditions

The stimuli used for this study were two 3-key "pop-up" toy pianos (Shelcore Inc.). Each of these was modified by attaching a 5 cm lever across the 3 piano keys. The lever sat 4 cm above the base of the piano, and pressing it down caused all 3 pop-up icons to be activated at once, making for a 3-way visual-auditory consequence on the piano top. The pianos and corresponding levers were also modified by covering them with brightly colored adhesive paper so the paper covering one piano had a pattern of red circles on a white background while the paper covering the other had a pattern of blue diamonds on a white background. These modifications made the two pianos visually distinguishable from one another. A final modification was that for each infant, the spring mechanism of one of the pianos was disabled, so that pressing its lever did not produce the audio-visual effect. This disabled piano served as the S- in the discrimination task, while the piano which "worked" was the S+. Which colored pattern marked the S+ and which marked the S- was counterbalanced across infants.

The two pianos were presented to infants simultaneously and side-by-side on each discrimination choice trial (see Fig. 1). In order to manipulate motor attention, the pianos were presented with their levers centered in reaching "slots" created with opaque Plexiglas partitions (7 cm × 5 cm) positioned to either side of each lever. The critical experimental manipulation to create differential motor control demands involved the width of the reaching slot formed by the partitions. In one condition, *Easy-Motor (EM)*, this distance was geared to the size of the infant's hand and allowed for 3 cm of lateral clearance on either side of the hand. With this arrangement, the levers could be easily pressed (and the S+ activated) by a wide range of reach-to-press actions; indeed, even a slapping action could result in a positive activation. In the second condition, *Hard-Motor (HM)*, the hand clearance was limited to 1.5 cm on either side. With this arrangement, simply slapping at the levers would not suffice because the hand would hit the partitions and thus fail to contact the lever embedded between them. Pressing the levers and activating the toy in this condition required a more refined posturing of the hand to reach through the slot and thus required more attentional effort for planning and executing the motor act. Importantly, the discrimination task, or cognitive demand, was always *identical* for both motor-task conditions: it involved tracking the S+ and selecting to press it rather than the S-.

2.1.3. Procedure and design

Parents and babies were invited to the laboratory where the procedure took place in a standard infant observation room. Each infant was seated on his or her parent's lap facing a stimulus presentation chamber (75 cm H × 75 cm D × 1 m L) which was designed to permit standardized and synchronized presentations of the two toys and also to block out extraneous visual information. A spring-loaded screen was built into the top front of the chamber and

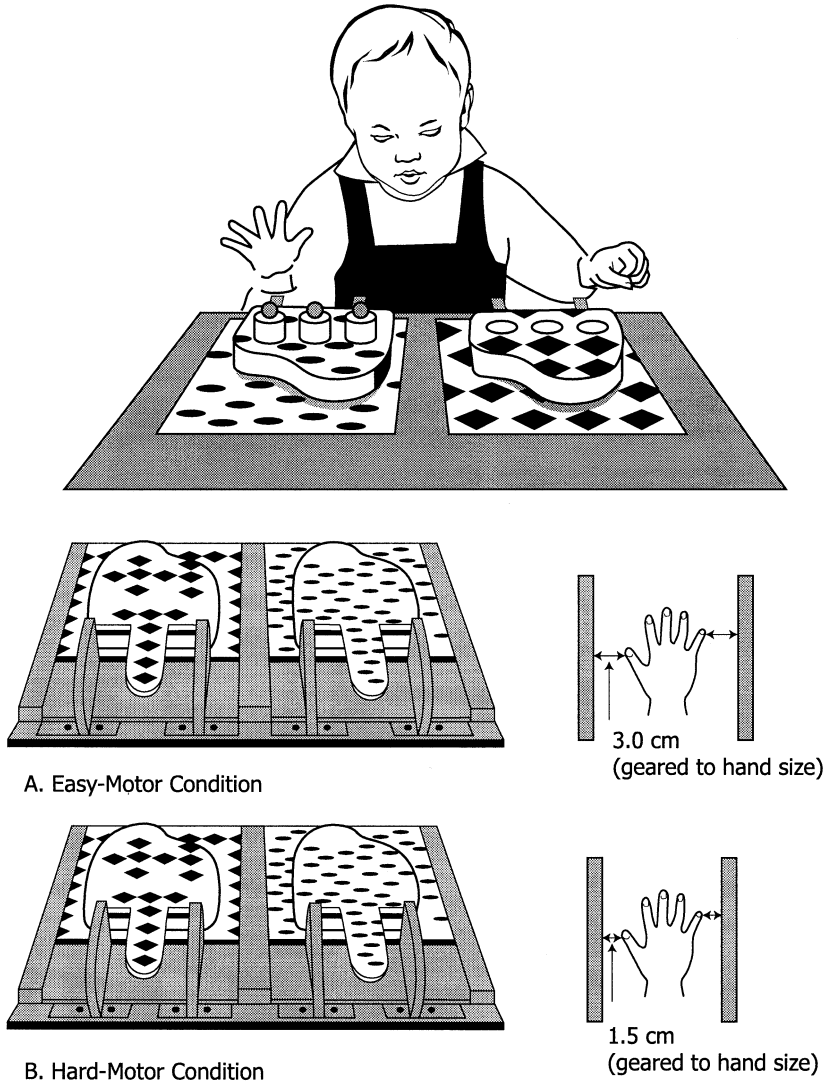


Fig. 1. Experimental setup for Study 1 illustrating the two motor conditions (A–B) and the hand-size adjustments made for each condition.

was pulled down by the parent between stimulus presentations. The toys were initially positioned about 15 cm from the infant’s hands (held on the parent’s lap) in the sagittal reaching plane. Infants first received 2 practice trials which involved the experimenter demonstrating the S + piano and encouraging the infant to try it. This practice period was followed by a series of 15 30-s experimental trials in one of the two motor-task conditions (*EM* or *HM*). Half of the infants participated in the *EM* task and the other half in the *HM* task. At the start of each trial, the parent lifted the screen and the S+ and S- toys were simultaneously moved along two sliding tracks (25 cm × 75 cm) by means of a push-rod, until they came to a full-stop in the infant’s reaching space.

The parent was instructed to gently hold the infant's hands below the front edge of the presentation chamber and to release them upon the experimenter's "go" signal once the toys were in position. The toys remained available to the infant until the S+ was activated, or until 30 s elapsed. The parent was permitted to prompt the infant to respond by saying: "Go get the music" or "Make the toy play," but of course was not permitted to point to the S+ or otherwise indicate which piano to contact. In addition to its audio-visual effect, activation of the S+ toy was followed by social reinforcement from both the parent and experimenter. When the trial was completed, the parent drew down the screen and the experimenter withdrew the pianos and arranged them for the next trial. The left/right position of the S+ toy was varied over trials according to an *ABBA-ABAB* sequence. The infant's behavior throughout the session was video-recorded by a two-camera (Panasonic WV 1800 series) system: one camera was positioned facing the infant to capture a frontal view and the other was positioned overhead to capture an ariel view on the reaching movements.

2.1.4. Scoring

The videorecords for each trial were scored for several behavioral and temporal measures formulated to capture discrimination learning rates. These measures included the following: (1) *response accuracy*: whether or not the infant reached first toward the S+ and succeeded in activating it; (2) *time-to-first touch*: the time (in secs) from the beginning of the trial to when the lever of either the S+ or S- toy¹ was first contacted (touched); (3) *time-of-S+ activation*: the time (in secs) from the beginning of the trial to the infant's activation of the S+ toy by pressing or banging the lever; (4) *S+ persistence*: the time spent at the S+ lever, actively pushing it in an apparent effort to make it work (before succeeding); and (5) *S- persistence*: the time spent at the S- lever, actively pushing it in an apparent effort to make it work. Reliability assessments (with blind review) were conducted on 20% of the total number of trials and yielded pearson *r* reliability coefficients of 0.82, 0.89, 0.82, and 0.76 for measures 2 to 5, respectively, all *p*'s < 0.05.

2.2. Results

The data analyses reported here are based on a final sample of 34 infants, 17 in each of the two motor conditions. Participants were included in the sample only if they responded by touching either the S+ or the S- piano on at least 10 of the 15 trials. Seven infants tested in the *EM* condition and 14 infants tested in the *HM* condition failed to meet this criterion. These infants had generally become fussy or disinterested in the task as the trials progressed.

2.2.1. Motor task validation

In order to validate the basic experimental manipulation, we compared the time-to-first-touch measure in the two motor conditions. A two-sample *t* test revealed a significant difference between the groups, $t(32) = -2.39$ $p < .01$. Infants in the *EM* condition took less time ($M = 3.9$ s) to reach forward from the start of the trial and touch one of the two levers than infants in the *HM* condition ($M = 5.13$ s). This result, in conjunction with a higher attrition rate from the *HM* condition (45% versus 29% from the *EM* condition) indicates that reaching through the narrower slots was, as intended, a more demanding task than reaching

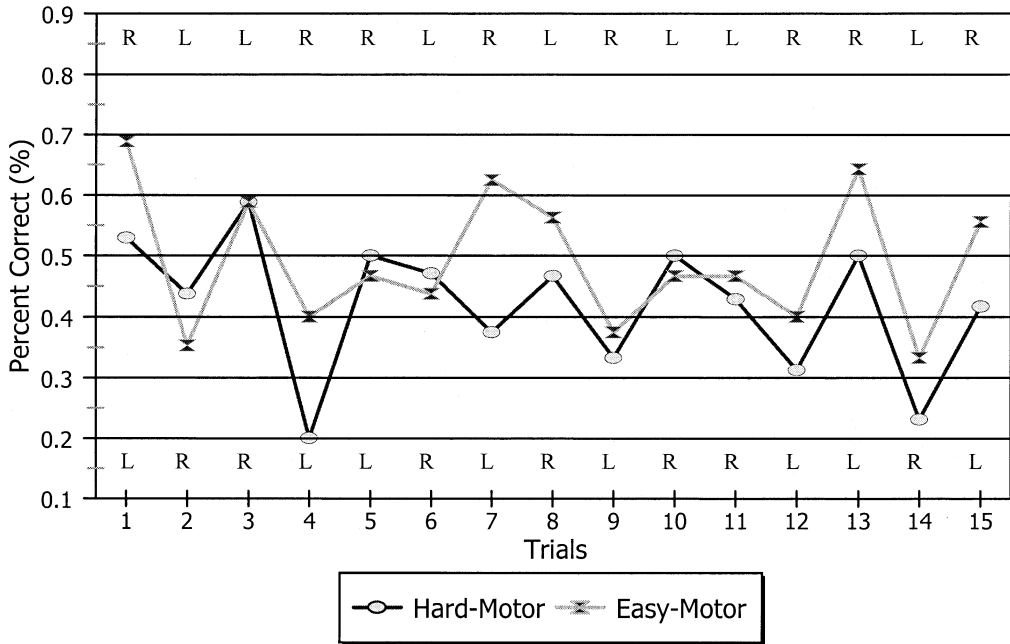


Fig. 2. Graph depicting the learning profiles for correct S+ responses over trials. Infants in the *Hard-Motor* condition reached through a narrower chute than infants in the *Easy-Motor* condition to press the S+ and S-levers. The letters L and R above the trial numbers indicate the left-right position of the S+ on each trial; either this sequence or the converse of it was used for each infant.

through the wider slots. That is, the *EM* task was indeed motorically “easier” than the *HM* task, and therefore presumably consumed less attention for the motor plan and control demands.

2.2.2. *Discrimination learning*

The proportions of infants who reached toward the S+ first and activated it out of the number who reached toward either of the pianos on each trial are shown in Fig. 2. Several things are apparent from this figure. First, in general greater proportions of infants were successful in the *EM* condition than in the *HM* condition; this was consistently so across trials later in the sequence. When the proportions correct across all trials were compared for the two conditions, a two-sample *t* test confirmed that infants in the *EM* condition ($M = 0.49$, $SD = 0.11$) were more successful than infants in the *HM* condition ($M = 0.42$, $SD = 0.11$), $t(28) = 1.757$, one-tailed $p < .05$. However, it is also apparent from Fig. 2 that infants did not seem to “learn” the discrimination, at least not in the classic sense of gradually increasing the likelihood of selecting the S+ over trials. Although infants typically worked at the task and activated the S+ piano sometimes in both conditions, their rate of success was no higher on trials toward the end of the sequence than at the beginning.

A hint regarding why infants did not show increased rates of success over trials comes from the abrupt “dips” in performance also apparent in Fig. 2, for instance at trials 4, 9, and 14. These drops in performance all occur on trials where the left-right position of the S+ was

changed from the previous trial, suggesting that infants may have been employing a sort of *win-stay* (at the same position) response strategy. This possibility is confirmed by an examination of infants' performance specifically on the trials which *followed* trials on which they had been successful. On these trials, infants in the *EM* condition went to the S+ on 15 of the 23 occasions when it remained on the same side as on the previous trial but went to the S+ on only 23 of the 72 occasions when its position was changed from the previous trial. Similarly, after a successful trial, infants in the *HM* condition went to the S+ on 16 of the 20 occasions when its position stayed the same but on just 21 of the 61 occasions when its position was changed.

Thus, once infants had made the S+ toy work, they were most likely to reach to the same left-right position on the next trial, being correct if the S+ was in the same position again, but being incorrect if its position had changed. This strong tendency to repeat a successful response may have prevented infants from showing any accumulating knowledge regarding which piano worked, especially as our scheme for counterbalancing the S+ position made for a large number of trials where it changed from the trial before.

2.2.3. Performance levels

While testing the infants, we did observe that in many instances, infants would initially reach toward one piano and then switch and reach toward the other one if their first choice did not produce the audio-visual reinforcement. Although such "second chances" are not ordinarily permitted in more standard-style discrimination tasks, this feature of our procedure allowed us to search further for evidence that infants did become aware of the difference between the S+ and S- pianos despite their response bias described above. We reasoned that switching to the other piano if the first choice did not produce an effect indicated a certain level of understanding that went beyond a simple random or aimless exploration of one piano or another. That is, we supposed that infants engaging in the switching behavior we observed were making a sort of "correction;" they had learned that just one of the toys worked and were acting purposefully to generate the reinforcing event. Accordingly, we devised a system for scoring infants' responses on each trial that takes this intermediate level of understanding into account, and then examined infants' performance across trials and in the two motor conditions again.

The finer-grained system for scoring infants' responses involved assigning a weighted score to each infant for each trial he or she completed, the score's value depending on the pattern of behavior the baby exhibited on that trial. The weighted scores ranged from 1 to 5 and incorporated which piano (S+ or S-) was touched first, whether a correction was made if the first-touched piano was S-, how quickly any such correction was made, and whether S+ was ultimately activated. The scoring system and brief rationales for each "performance level" are provided below:

Level 1 ("No Go") = the infant either touches S+ first but never activates it *or* touches S- first and does not switch to S+. This behavior gives no indication that the infant expects any effect from touching either piano and is not distinguishable from exploratory behavior.

Level 2 ("Slow Switch") = the infant touches S- first but then after a long delay² switches to S+ and activates it. This behavior may indicate that the infant expects an effect from

touching at least one of the pianos, or it may simply be exploratory, but in any event it provides the infant with information on which to build an expectation.

Level 3 (“Fast Switch”) = the infant touches S- first but then after a short delay goes directly to S+ and activates it. This behavior indicates an expectation on the infant’s part that touching one of the pianos will produce an effect; the infant seems to know that if the first toy touched doesn’t work, then the other one will.

Level 4 (“Slow Activation”) = the infant touches S+ first and activates it, although after a long delay. This behavior indicates that the infant expects the S+ piano in particular to work, but may not know precisely how to make it work.

Level 5 (“Fast Activation”) = the infant touches S+ first and activates it right away. This behavior indicates that the infant expects the S+ piano in particular to work and also knows just how to make it work.

Once the data had been scored according to this performance level scheme, a number of analyses were carried out on these measures. First, a straight-forward conditions by trials ANOVA was conducted. This yielded a significant condition effect, $F(1,32) = 4.82, p < .05$. Infants in the *EM* condition ($M = 3.04$) had higher performance level scores overall than infants in the *HM* condition ($M = 2.72$). Neither the trials effect nor the condition by trials interaction in this analysis was significant. When the 15 trials were grouped into three blocks of 5 trials each, infants in the *EM* condition showed only a modest and non significant increase in performance scores over the three blocks ($M_s = 2.96, 3.05, \text{ and } 3.11$, respectively) and infants in the *HM* condition showed no improvement ($M_s = 2.75, 2.76, \text{ and } 2.68$, respectively). The lack of improvement over trials may again reflect a strong interfering effect from the response bias already described, which would have depressed performance on certain of the later trials.

We also used the performance level scores to identify “critical learning runs” (CLRs) of several trials in succession with performance scores of 3 or higher. The score of 3 was used as the watershed score here because it is the lowest performance value which clearly implicates purposeful behavior (beyond exploration) on the infant’s part. The runs idea was adapted from Roder, Bushnell, and Sasseville (2000) “critical novelty run” measure and is based on the argument that while a single trial with a high score might just be happenstance, several such trials in a row are unlikely to occur by chance. Furthermore, any three trials in a row always included at least one instance of the S+ piano changing its left/right position, so a run of three or more trials all with high performance scores suggests that the infant appreciated the discrimination enough to override the response bias also operating.

With the CLRs identified in the data, we first noted how many trials comprised the longest such run exhibited by each infant, and compared this index across the two motor conditions. The longest runs of high-level performance for infants in the *EM* condition were on average 3.00 trials long ($SD = 1.17$) and were significantly longer than those for infants in the *HM* condition ($M = 2.24$ trials, $SD = 1.03$), $t(32) = 2.018$, one-tailed $p < .05$. Next, we considered individual rather than grouped data and noted that 10 of the 17 infants in the *EM* condition had at least one CLR of 3 or more trials and 4 of these infants had two separate CLRs of at least 3 trials. In comparison, only 7 of the 17 infants in the *HM* condition had CLRs of 3 or more trials and none of them had more than one. Moreover, infants who had CLRs of at least 3 trials in the *EM* condition began these runs earlier in the sequence of trials

(M onset = Trial 4.2, $SD = 3.5$) than infants with such runs in the *HM* condition (M onset = Trial 7.0, $SD = 4.4$), although this difference only approaches significance ($t(15) = -1.39$, $p = .09$) due to the small number of infants involved. In general then, all of the analyses involving CLRs of high performance scores as well as the analysis on the performance scores across all trials point to the conclusion that infants in the *EM* condition learned the discrimination task more effectively—that is, to a higher level and also more quickly—than infants in the *HM* condition.

2.2.4. Persistence measures

Lastly, the two motor conditions were compared for the S+ and S- persistence measures. There was no difference in time persisting (unsuccessfully) at the S+ between the two motor conditions. This is not surprising, as most infants had little trouble activating the piano toy once they clearly intended to do so. The average S+ persistence time in both conditions was accordingly quite short, $M = 1.53$ secs for the *EM* condition and $M = 1.57$ secs for the *HM* condition. Thus, while getting to the lever of either the S+ or the S- may have been difficult in the *HM* condition, as was learning that the S+ was the piano to go to, actually pressing the lever once at the S+ was not difficult. With regard to time persisting at the S-, there was a significant difference between the two motor conditions, $t(32) = 1.75$, $p < .05$. Infants in the *HM* condition spent more time ($M = 4.82$ secs) working at the S- toy apparently attempting to produce an effect than infants in the *EM* condition did ($M = 3.80$ secs). This finding indicates that learning the negative value (i.e., that it affords no reinforcement) of the S- was compromised in the *HM* condition, and thus corroborates the other findings framed with reference to S+ but likewise indicating that the cognitive task of discrimination learning may be interfered with by motor task demands.

2.3. Experiment 1 discussion

Overall, it was impressive to see that babies at this age did not exhibit the classic discrimination learning pattern; they appear to have difficulty planning and executing what was thought to be a simple discrimination and therefore did not perform as predicted. Since we know that infants are capable of learning similar visual discriminations (Colombo et al., 1990), it seems a reasonable conjecture that the difficulty for the infant originated with the additional effort required for carrying out the intermediary motor execution portion of the task. The results with the new levels of learning performance scores and the CLR analyses suggest that infants in the *HM* condition exhibited compromised, or reduced discrimination learning, in comparison to the infants in the *EM* condition, thereby fundamentally supporting the hypothesis that when infants are forced into a demanding motor act, attentional resources are commandeered from the ultimate purpose or cognitive goal of the action itself, in this case solving a visual discrimination. In short, attentional resources normally devoted to the end-state are *spilled forward* to deal with the motor planning and task execution demands, demonstrating a trade-off between reaching demands and learning success.

In regards to the response strategy bias, it is first important to note that the learning effects between motor conditions were influenced equally and thus the response strategy does not

ameliorate the above interpretations regarding motor load and attention. It should also be noted that we think this type of response strategy can be best explained in the context of motoric constraints or motor ritualization. For example, from the dynamical systems perspective Thelen and Smith (1994) argue that infants have a tendency to repeat movements with similar kinematic properties as part of a *motor attractor* system. Reporting on the \overline{AB} error, Hofstadter and Reznick (1996) showed that infants 7 to 11-months were more apt to make the \overline{AB} error when the index of performance was a reaching action rather than a glancing action (gaze direction); strong reaching position biases were also found. Perseveration errors have a protracted developmental window into preschool age for some physical knowledge tasks involving object gravity rules (Hood, 1998). Thus, while infants' attenuation in learning the S+/S- discrimination over time can be explained in part from a motor perseveration or motor dynamic bias perspective, infants in the *HM* condition selected the correct toy less often than infants in the *EM* condition.

While Experiment 1 illustrated the effects of increased motor demands on a cognitive goal involving a discrimination learning task, Experiment 2 was designed to explore the complementary question: what are the effects of increased cognitive demands on the planning and execution of a reaching act? More precisely, can attentional resources be diverted from motor planning and reaching performance to accommodate the demands of a challenging cognitive goal? In this study, 10½-month-olds were required to solve a Piagetian-style means-ends problem. In order to isolate the attentional effects of problem-solving demands on motor planning and task execution, the *cognitive demands were manipulated* while the motor demands were held constant. It was hypothesized that motor planning and execution would be reduced when the cognitive demands were heightened.

3. Experiment 2

3.1. Method

3.1.1. Participants

Thirty-four full-term 10½-month-olds (15 females, 19 males) all born within 2 weeks of their calculated due dates served as the research participants. By this age, infants have a demonstrated ability to perform planned means-ends tasks requiring up to three or more subgoals (Willatts & Rosie, 1989; Willatts, 1990, 1999) and are motivated to produce coordinated prehension acts to retrieve a goal-toy. Procedures for recruiting infants were identical to those employed in Experiment 1.

3.1.2. Stimuli and apparatus

The stimuli used for this study consisted of small hand-sized goal-toys (people and animal characters varying in color and features), which were presented on a stimulus tray (Plexiglas construction) designed to fit the presentation chamber described in Experiment 1. The stimulus tray moved along two sliding (built-in) tracks within the infant's reaching space. The goal-toy could *only* be retrieved by pulling a short graspable soft cord (1 cm diameter \times 22 cm) which was attached to the sliding stimulus tray. The end of the "pull-cord" was

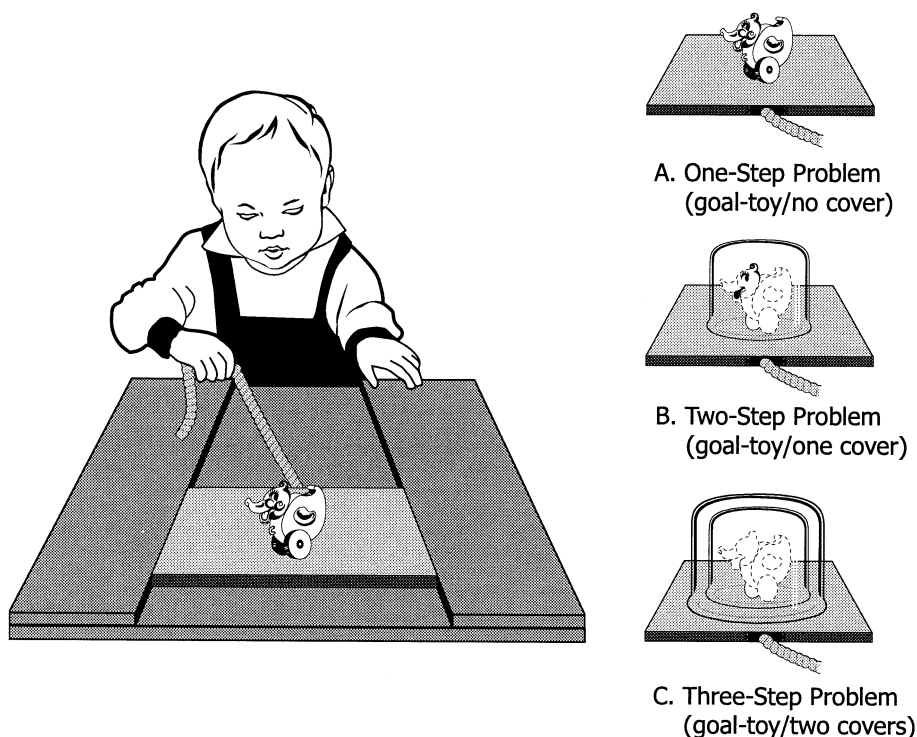


Fig. 3. Experimental setup for Study 2 illustrating the three problem types (A–C) with the opaque covers and toy depicted as “transparent” to reveal the embedded elements.

positioned 12 cm from the edge of the table surface in the infant’s sagittal reaching plane and approximately 7 cm from the infant’s hands on the parent’s lap. Opaque toy covers consisted of stacking boxes (Playschool Stacking Cups) with small (2 cm × 2 cm) lego blocks attached at the top to provide a small “handle” for lifting the cover. By design, the stacking boxes permitted goal-toy embedded conditions wherein one or more covers could conceal the goal-toy. All toys and covers were secured to the stimulus tray by means of small velcro tabs, which required minimum force to release the bond. Any one goal-toy was approximately 40 cm from the infant’s hand, thus necessitating the use of the cord in order to reach the target goal-toy (see Fig. 3).

3.1.3. Means-ends task conditions

The goal-toys were presented in one of three means-ends or problem type conditions meant to be differentially complex according to the amount of attention that the infant might consume in the process of task completion. In the simplest condition (*1-step*), the toy was positioned on the tray by itself. In a second condition (*2-step*), the toy was positioned on the tray and then covered with an opaque stacking box. The third condition consisted of two versions of a 3-step means-ends problem. In one version (*3-step-a*), the toy was positioned on the tray and covered with an opaque stacking box which was then itself covered with a second opaque stacking box. In the second version (*3-step-b*), the toy was positioned under

one of two opaque stacking boxes, which were positioned in spatially distinct locations (7 cm apart at the center line of each stacking box). Presumably, 3-step problems required more focused attentional effort or mental focus than did the 1-step problems since they consisted of multiply embedded elements which had to be mentally “attended to” at every subgoal along the way if the infant wanted to achieve the goal-toy reward. Importantly, the necessary action or motor preparation (i.e., the *pull-phase*) was *identical* for all three problem type conditions. In other words, the initiation of the reaching action and initial contact with the pull-cord was no more demanding in 3-step than 1-step problems. Therefore, while the end-state elements changed between conditions, the manner in which to begin the *subgoaling* (Willatts, 1990) aspect of the process was the same for each problem type.

3.1.4. Design and procedure

Each infant received 2 practice trials which involved encouraging the infants to pull the cord and tray towards themselves to obtain a goal-toy. This practice period was followed by 3 blocks of 3 experimental trials each for a total of 9 (30-s) trials with all infants experiencing all problem types, including the two versions of the 3-step problems. The first trial of each block always contained a 2-step problem and was then followed by either a 1- or 3-step problem. The 2-step problem presented in the first trial provided a middle standard for the critical comparisons between 1- and 3-step problems (i.e., easy vs. hard—similar to the easy vs. hard motor conditions in Study 1). The second and third trials of each block were counterbalanced within and between trial blocks for the 1- and 3-step problems.

The standard procedure for all 3 problem types involved physically demonstrating the task to the infant in a “game-like” fashion by hopping the goal-toy across the table onto the specified position on the presentation tray. In the 2 and 3-step problems, the requisite stacking covers were added with deliberate movements and narration to ensure the baby’s attention to the goal-toy demonstration. The procedure followed scripted instructions equal in verbal length for all three conditions. As a standardized control procedure, the experimenter’s demonstration and presentation of the 1-step problem took approximately the same amount of real time as the more involved demonstration of the 3-step problems. In other words, the experimenter deliberately added “redundant” verbal information and elongated the physical demonstration in the 1- and 2-step problems so the “delay” between the start of the demonstration and the start of the reach was the same for all three problem types ensuring that the demonstration time alone would not create a memory or performance (dis)advantage for any one problem type.

During the stimulus presentation, the parent was instructed to gently hold the infant’s hands at the lower edge of the experimental chamber until the experimenter placed the pull-cord at the preset distance in front of the infant. Once the experimenter released the cord, the verbal command “Okay, [name], you get the [toy name]” was issued, which signaled to the parent to release the baby’s hands. When the infant successfully pulled the cord and retrieved the goal-toy, they received social reinforcement from both the parent and experimenter. For infants who did not pull the cord or retrieve the goal-toy within the 30-s trial window, the stimulus tray was retracted and no verbal and social encouragement was offered. Each infant’s behavior throughout the session was video-recorded by the same two-camera system as described in Experiment 1.

3.1.5. Scoring

The videorecords for each trial were scored according to a series of behavioral and temporal measures assessing the pull-to-obtain phase of the tasks. These measures were formulated to capture motor planning and control, and included the following: (1) *time-to-first-touch (FT)*: the time from the beginning of the trial, when the pull-cord was positioned by the experimenter, to the infant's first contact (touch) with the pull-cord; (2) *time-to-first-pull (TFP)*: the time from the first touch of the cord to the first successful pull of the cord which resulted in forward movement of the stimulus tray; (3) *time-to-goal-touch (TGT)*: the time from the first pull of the cord to the first contact with the visible object on the stimulus tray (i.e., either the goal-toy in the 1-step condition or the outermost cover in the 2- and 3-step conditions); (4) *number of separate grasps (NSG)*: the number of individual or distinct grasps (with either hand) of the pull cord, separated by a release of the cord, which occurred prior to the goal-touch. One cycle of grasping and then releasing the cord counted as one separate grasp (this measure captured any "fumbles" or broken contacts with the pull-cord); and (5) *number of bimanual reaching shifts (NBS)*: the number of 2-handed or hand-over-hand pulls during the pull-to-obtain phase of the task (i.e., up to the goal-touch). Pulling the cord with one hand along with or followed by pulling with the other hand counted as one instance of bimanual reaching activity; more than one such instance could be captured by this measure. Reliability analyses (with blind review) on 20% of the total number of trials indicated Pearson r reliability coefficients of 0.87, 0.95, 0.93, 0.91, and 0.89, for these five measures respectively, all p 's < 0.05.

3.2. Results

The data analyses reported here are based on a final sample of 27 infants. Participants were included in the sample only if they completed at least the first 2 of the 3 trial blocks. Seven of the 34 infants tested failed to meet this criterion because they became fussy or disinterested in the task as the trials progressed. Also, preliminary analyses indicated that there were no important differences between performance on 3-step-a and 3-step-b problems for any of the measures. Hence, the data for the two versions of 3-step problems were collapsed and treated as one generic kind of 3-step problem in the analyses reported below.

3.2.1. Means-ends performance

Infants generally were able to solve both the simple and the multiple-step problems by acting appropriately toward the successive subgoals to eventually reach the end-point of attaining the little toys. That is, they engaged in goal-based problem solving by first contacting the pull-cord, then pulling it to move the tray closer to themselves, and then retrieving the goal-toy which sometimes involved lifting one or more covers first. While it was not the focus of this study, it is important to note that infants seemed to be intentionally working toward the final task solutions in these problems, as evidenced by their task persistence, error-correction, and constant vigilance of the goal-toy area (cf. Willatts, 1990, 1999). As for the preliminary pull-to-obtain phase which was the focus of this study, this phase was completed by the infants on 84% of the 1-step problems, 95% of the 2-step problems, and 79% of the 3-step problems. The number of infants completing the pull-to-

Table 1

Summary table of means (in seconds) for the temporally related dependent measures (FT = *Time-to-first-touch*; TFP = *Time-to-first-pull*, and TGT = *Time-to-goal-touch*) across trial blocks (1–3) and level of task difficulty indicated (1–3). Standard deviations are presented in parentheses

Measure		Trial Block 1	Trial Block 2	Trial Block 3
FT	1-step	1.22 (1.12)	0.89 (0.54)	0.65 (0.29)
	2-step	3.23 (5.07)	0.93 (0.65)	0.68 (0.30)
	3-step	2.59 (1.31)	1.29 (0.97)	0.75 (0.39)
TFP	1-step	1.18 (1.02)	0.79 (0.89)	0.56 (0.20)
	2-step	1.33 (1.56)	1.08 (1.36)	0.71 (0.65)
	3-step	1.74 (1.05)	0.81 (0.72)	0.60 (0.33)
TGT	1-step	2.53 (1.77)	2.19 (1.25)	2.40 (1.31)
	2-step	3.71 (3.23)	2.81 (2.33)	2.10 (1.09)
	3-step	2.77 (1.66)	2.64 (1.81)	2.11 (1.15)

obtain phase for all three problem types declined somewhat by the third trial block, suggesting that some of them had lost interest in the task by that point.

3.2.2. Timing measures

For all the trials on which infants did complete the pull-to-obtain phase, the mean times to accomplish the various portions of this phase for the different types of problems and for the three trial blocks are displayed in Table 1. Three (blocks) by 3 (difficulty level) ANOVAs were conducted on the times for each portion of the pull-to-obtain phase, as well as on the overall times for the whole pull-to-obtain phase. Each of these ANOVAs yielded a significant blocks effect: $F(2,52) = 16.61, p < .001$ for the time-to-first-touch measure, $F(2,52) = 14.90, p < .001$ for the time-to-first-pull measure, $F(2,52) = 3.11, p = .05$ for the time-to-goal-touch measure, and $F(2,52) = 21.77, p < .001$ for the composite times across the whole pull-to-obtain phase. As is clear from Table 1, for all problem types, infants generally got faster at completing each portion of the pull-to-obtain phase across the three trial blocks. This decrease over trials in the time taken to grasp and pull the cord can be interpreted as a learning or skill automatization effect; with successive trials, infants evidently mastered the motor component of grasping and pulling the cord to bring the tray in.

The critical manipulation in Study 2 involved the different levels of task difficulty subsequent to pulling the tray in. To examine whether task difficulty had any effect on the prior motor planning and control demands required to accomplish the tasks, we compared the time taken in each portion of the pull-to-obtain phase on 1-step problems to that on 3-step problems. Performance on the 2-step problems was not included in these analyses because the 2-step problem was always presented first within each trial block; hence it might be expected to have longer execution times than the other problems, particularly in light of the robust practice effect documented in the omnibus ANOVAs. Also because of the practice effect, we compared performance on the 1-step versus the 3-step problem types separately within block 1 and block 2; performance on the third block was not considered further because infants' pull-to-obtain times had clearly "bottomed out" by that point in the session (see Table 1).

The overall time infants took from the start of the trial to grasp the cord, pull the tray in,

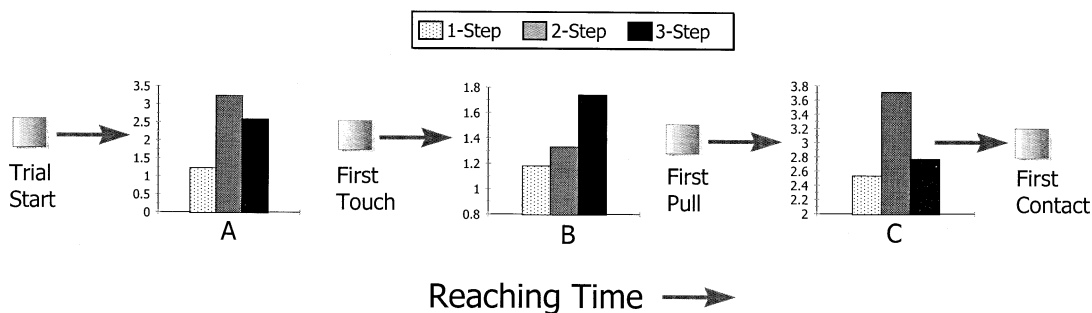


Fig. 4. Graph depicting the temporal measures of (A) *time-to-first touch*, (B) *time-to-first pull*, and (C) *time-to-goal-touch* for trial block 1 across the three problem types. Bar graphs for each measure are positioned within a schematic of the reaching time sequence spanning from trial start time to first object (either the goal-toy in 1-step problems or the an outermost cover in 2- or 3-step problems) contact time.

and contact either the toy (1-step problems) or the outermost cover (3-step problems) was significantly longer on 3-step problems than on 1-step problems in both blocks 1 and 2. On block 1, infants took an average of 7.12 secs ($SD = 1.88$) on 3-step problems but only an average of 4.95 secs ($SD = 2.27$) on 1-step problems, $t(26) = 4.70$, one-tailed $p < .001$. Similarly, on block 2, infants took an average of 4.85 secs ($SD = 2.04$) on 3-step problems but only an average of 3.88 secs ($SD = 1.58$) on 1-step problems, $t(26) = 2.1$, one-tailed $p < .025$. When the several components of the pull-to-obtain phase were considered individually, infants' time-to-first-touch was significantly longer on 3-step problems than on 1-step problems in both blocks 1 and 2. The means for these components are shown in Table 1; for block 1, $t(26) = 4.56$, one-tailed $p < .001$, and for block 2, $t(26) = 1.89$, one-tailed $p < .05$. Thus, infants took more time just to initiate their solution effort and get their hands to the pull-cord when confronted with the 3-step tasks in comparison to the 1-step tasks. Once they had touched the cord, infants' time-to-first-pull was likewise longer on 3-step problems than on 1-step problems, but only significantly so on block 1, $t(26) = 2.20$, one-tailed $p < .025$. Infants' time-to-goal-touch was not significantly different on the two kinds of problems in either block 1 or block 2, although the differences in each case are in the predicted direction (see Table 1). In general, the results for the timing measures are consistent with the central hypothesis of Study 2, namely that the increased attentional demands of the multistep means-ends problems would influence motor planning and execution, in this case by protracting it. These results were especially robust in the first block of trials, before infants had become practiced at the pull-to-obtain maneuver; for emphasis, the block 1 results are graphically illustrated in Fig. 4 across the reaching time sequence.

3.2.3. Manual behaviors

The final set of analyses for Study 2 involved the two manual measures, number of separate grasps (NSG) and number of bimanual reaching shifts (NBS). The results for these two measures for the different types of problems and the three trial blocks are displayed in Table 2. A 3 (blocks) by 3 (difficulty levels) ANOVA on the number of separate grasps revealed no significant block or difficulty effects. Thus, infants did not seem to change the number of separate grasps they used on the cord as the trials progressed, and although they

Table 2

Summary table of means for the manual dependent measures (NSG = *Number of separate grasps* and NBS = *Number of bimanual shifts*) across trial blocks (1–3) and level of task difficulty indicated (1–3). Standard deviations are presented in parentheses

Measure	Trial Block 1	Trial Block 2	Trial Block 3
NSG 1-step	1.25 (0.52)	1.13 (0.34)	1.38 (0.77)
2-step	1.37 (0.56)	1.34 (0.55)	1.17 (0.38)
3-step	1.40 (0.57)	1.35 (0.73)	1.04 (0.21)
NBS 1-step	0.29 (0.54)	0.30 (0.55)	0.50 (0.61)
2-step	0.48 (0.63)	0.44 (0.57)	0.30 (0.55)
3-step	0.64 (0.63)	0.50 (0.57)	0.23 (0.53)

used slighter greater numbers of grasps on the 3-step problems than on the 1-step problems in blocks 1 and 2, these differences were not significant. An analogous ANOVA on the number of bimanual shifts likewise revealed no significant block effect, but suggested that infants may have used both hands more frequently on the more difficult problems. Separate within-block analyses yielded a significant effect of difficulty in block 1, $F(2,25) = 2.10$, $p < .05$, but not in blocks 2 or 3. An LSD posthoc test with $p < .05$ indicated that the significant difference in block 1 was between performance on the 1-step problems and on the 3-step problems; infants employed two-handed pulling strategies more often when dealing with the attention-demanding 3-step tasks.

3.3. Experiment 2 discussion

For all of the results reported for Experiment 2, the effects were strongest for trial block 1, moderated for trial block 2, and nonexistent for trial block 3. This pattern of responding suggests a practice or learning effect such that initial demands of attending to differentially complex goal-states became *automatized* early for this means-ends task. However, the differences reported for trial block 1, and sometimes for trial block 2, are crucially linked to the questions addressed in this study. Infants' performance on the means-ends task was very impressive and supports findings by Willatts (1990) that infants under 12-months can exhibit *planned* and *planful* solutions to multistep means-ends problems. Moreover, the rapid learning and automaticity of basic goal success also supports recent findings by McCall and Clifton (1999) who demonstrated how infants from 8½ months can solve complex means-ends search tasks even in the dark.

Most central to our predictions, the reported evidence in this study fundamentally supports the hypothesis that when infants are forced to attend to a demanding task requiring them to remember the toy's location or to think ahead about how to uncover the toy, attentional resources are commandeered from the requisite motor planning and task execution. In this case, the reaching performance for goal-toy acquisition becomes compromised. In short, attentional resources normally devoted to the motor planning and execution are *spilled forward* to deal with end-state cognitive demands, demonstrating a trade-off between planning ahead and task execution. These findings, in concert with the findings from Experiment 1 provide a new context for discussing perception-action couplings in infancy.

3.4. General discussion

The research reported in these studies provides the first systematic investigation of how attentional focus and resource allocation are configured within the developmental frame of infants' goal-directed actions. These experimental findings support what we have termed the attention-driven *cognition/action trade-off*, with either motor or cognitive performance enhanced or depressed depending on the location of the attentional focus or Treisman-like "spot-light." More specifically, results document a particular aspect of the critical relationship between thinking and moving during the sensorimotor period of human development: namely, that planning for and anticipating future-oriented goals can compromise the very actions which work in service of these goals, while likewise planning for and deploying actions can also compromise the very end-state goals the actions were directed to. Taken together, these results suggest that as perception-action couplings for goal-directed behavior emerge during infancy, cognition and motor skills must compete for the limited and valuable attentional resources available for acting purposefully on the world of objects.

Our approach in this research was to document how thinking and acting are coupled during a crucial time in infancy when a confluence of perceptual-motor skills are undergoing important development. Therefore we examined an important perception-action coupling by synchronically isolating the focus of attention within emerging motor skills, rather than presenting a diachronic analysis resulting in a developmental time-line. However, we stipulated that the same kind of trade-off might be similarly shown in the context of adults learning a new motor learning task (e.g., learning to drive a motor car with a manual transmission wherein complicated hand-foot coordination is involved). For infants though, such resource allocation comes into play far more pervasively since fundamental motor skills like reaching are still emerging and implicated in numerous developmental tasks that are integral to cognitive advancement in the first year. Hence, our findings involving the *cognition/action trade-off* proposal allow motor development and motor attention to assume a higher "stature" in developmental studies and are thus potentially felicitous for explaining a broad range of developmental outcomes. In particular, the results of this study can be examined in, and have implications for, the following research nodes: *Object Search and Cognitive Demands*; *Concurrent Acts and Motor Demands*; and *New Perception-Action Coupling Explorations*.

3.4.1. Object search and cognitive demands

The past decade has seen a dramatic resurgence of interest in Piaget's classic $A\bar{B}$ search error. As noted previously, several explanations have been presented in an attempt to explain this unique cognitive expression: perseverative errors within specific tasks constraints (Hoftstadter & Reznick, 1986); a dynamic motor-attractor (Smith et al., 1999); and dorsolateral prefrontal cortex immaturity and inhibition tendencies to previously rewarded responses (Diamond et al., 1994; Diamond, 1995). Findings reported in $A\bar{B}$ studies, in part, help explain why infants capable of a basic visual discrimination failed to demonstrate cumulative discrimination learning over trials in Study 1 as the motor dynamic bias tended to override whatever the infant might have known about which of the pianos worked. At the same time, the attention-driven *cognition/action trade-off* may alternatively shed new light on the $A\bar{B}$

error and object search tasks in general. For example, the consumption of selective attention by the demanding search aspect of the task might explain the poor cognitive or representational aspect of the task. From a neuropsychological model, Bell and Adams (1999) have recently explored the interacting effects of working memory, inhibition, and attention to show how looking and reaching versions of the $A\bar{B}$ task might be construed to yield similar results at 8-months. Emerging from these studies is also the fundamental question about how knowledge ultimately informs, or conversely, fails action (e.g., see Berthier et al., 2000). Finally, we believe our findings are consistent with Munakata and her colleagues (e.g., Munakata et al., 1997), who have introduced the notion of *graded representations* for explaining the differences and errors between object recognition and object search tasks. Indeed, cognitive load does influence elements of the reaching plan as demonstrated in Experiment 2.

3.4.2. *Concurrent acts and motor demands*

In both studies infants were effectively asked to divide their attentional resources to deal with an increased motor or cognitive demand. There are relatively few accounts of manipulating infant attention for concurrent demands (e.g., walking and talking; finger tapping and recitation, etc.). The results reported here corroborate a number of research findings documenting concurrent task interference effects in older subjects: for finger-tapping and speaking rates in older children (e.g., Hiscock et al., 1985); for information-processing accounts of capacity allocation and memory in older children (e.g., Manis et al., 1980); and for numerous interference effects involving complex motor-control behavior in adults (e.g., Reason, 1984; Schmidt, 1988). Similarly, our current findings are consistent with the modality-specific interference effects observed in adults (Halpern, 1990; Pashler, 1990) in which attention is effectively “drained” from one system to enhance performance in another, and also consistent with analogous research directed to uncovering action-based mechanisms of adult attention (Tipper et al., 1999).

Additionally, as Bushnell and Boudreau (1993), and more recently Diamond (2000) have pointed out, cognition has tended to be accorded a more superior or “exalted status” (Diamond, 2000, p. 44) in contrast to motor development. The current study with its principal focus on the parallelling influence of action and cognition lends important legitimacy to the contribution of motor attention in the perception-action coupling. Other infancy researchers are also beginning to acknowledge this new emphasis. For example, Needham (1999) has recently shown that infants’ stored interpretations of visual displays of object presentation events influenced and guided future reaching action. She reported that 12½ month-olds produced the same actions as previously displayed but that the 9½ month-olds did not. In explaining the results, among other interpretations, Needham suggests that cognitive resource limitations and cognitive load demands of advanced reaching behavior could explain the developmental differences.

3.4.3. *New perception-action coupling explorations*

This special issue on *Perception-Action Coupling in Infancy* is a tribute to the engaging dialogue we presently enjoy across a variety of disciplines devoted to unpacking the complex contribution of perception and action for intellectual advancement. Additionally, recent

reviews and full-length studies of perception, action, and coordination (e.g., Bloch, 1998; Bertenthal & Clifton, 1998; Thelen, 2000, Thelen & Smith, 1994), as well as engaging debates on the Piagetian theory (e.g., Russell, 1999), object concept (e.g., Baillargeon, 1999), and means-ends problem-solving skills (e.g., Willatts, 1999), have substantially widened the developmental stage for exploring new theoretical and experimental ground around the perception-action coupling. As case in point, we have examined the exploratory and exploitative functions of the hand for haptic perception and tool-use development (Bushnell & Boudreau, 1998); McCarty et al. (1999) have explored functional everyday action-selection strategies during early and late infancy; and most recently Lockman (2000) has suggested that given recent advances in perception-action research, it is now an opportune time to re-examine the developmental roots of tool-use. Specifically, Lockman suggests a Gibsonian perspective to examine the affordances of tool-surfaces or tool-object combinations.

Finally, the current research also invites questions for further study. First, our findings need to be confirmed across a diversity of task constraints, perhaps with the added rigour and precision of a kinematic analysis. For example, findings by Lin, Wu and Trombly (1998) showing that adult reaches for functional or ecologically relevant goals generate better quality kinematic profiles than do reaches directed to goals with less functional relevance hold much promise for similar studies with infants. Second, critical transition points in development would be particularly important to examine within the attentional context proposed. For example, Corbetta (1998) has suggested that the transition to upright locomotion may interfere with previous established patterns of coordination in reaching: how might our findings be implicated in such vital transitions in development? Third and ultimately, the human infant may well demonstrate adeptness in a discrete sensory, perceptual, or action domain, and may also possess a particular conceptual knowledge and agency. However, as our results show, whenever developmental advances require embeddings or coordinations of such separate competencies, as is prototypically the case for developmental milestones that characterize infancy, the idea of “spilling thoughts” or the attention-driven *cognition/action trade-off* must be incorporated into our conceptualizations of perceptual-motor development.

Notes

1. Determining the precise time of the start of an infant's reach is a well documented challenge in the literature. Consistent with similar studies (e.g., von Hofsten & Rönnqvist, 1988; Out et al., 1997) the start of the reach was operationally defined from the first video frame of forward hand movement directed towards the target after the target was visually engaged by the infant as it was moved to the specified presentation location following the “go” command as described in the procedure.
2. Criteria for defining a fast switch and a slow switch for each motor condition were based on the overall mean differences between conditions for *time-to-first touch* (i.e., 1.23 s). In other words, given this time difference, infants in the *HM* condition were given a wider time-response window (Fast = ≤ 4.73 s; Slow = ≥ 4.73 s), whereas infants in the *EM* condition were given a smaller time-response window (Fast = ≤ 3.50 s; Slow = ≥ 350 s).

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