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Rats' learning of a new motor skill: Insight into the evolution of motor sequence learning

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Abstract

Recent behavioral and neural evidence has suggested that ethologically relevant sub-movements (movement primitives) are used by primates for more complex motor skill learning. These primitives include extending the hand, grasping an object, and holding food while moving it toward the mouth. In prior experiments with rats performing a reach-to-grasp-food task, we observed that especially during early task learning, rats appeared to have movement primitives similar to those seen in primates. Unlike primates, however, during task learning the rats performed these sub-movements in a disordered manner not seen in humans or macaques, e.g. with the rat chewing before placing the food pellet in its mouth. Here, in two experiments, we tested the hypothesis that for rats, learning this ecologically relevant skill involved learning to concatenate the sub-movements in the correct order. The results confirmed our initial observations, and suggested that several aspects of forepaw/hand use, taken for granted in primate studies, must be learned by rats to perform a logically connected and seemingly ecologically important series of sub-movements. We discuss our results from a comparative and evolutionary perspective.

Keywords

Motor skill learning; Reaching; Grasping; Movement primitives; Temporal order; Evolution

1. Introduction

Since Wolfgang Kohler's famous experiments on chimpanzee problem solving and "insight" (Köhler and Winter, 1926), comparative psychologists have questioned Kohler's experimental interpretations and have investigated similar, apparently insight-driven motor learning processes with greater scientific rigor (Chance, 1960; Epstein et al., 1984; Windholz, 1984). In one of the most oft-cited experiments, Kohler placed a banana hanging from the ceiling beyond the chimpanzees' reach. After failing to obtain the banana by jumping from the ground, some chimps appeared to sit quietly for a moment, then would jump up and pile crates from a distant part of the room on top of one another under the fruit, creating a sort of stepping stool that allowed them to grasp the prize. Although Kohler argued that the chimps' learning process involved genuine insight, further experiments with chimps, pigeons and other species have instead supported the notion of a learning process based on prior Pavlovian and operant conditioning, and Thorndikian trial-and-error learning (Epstein et al., 1984; Windholz, 1984). Thus, Kohler's "insight" experiments are more accurately described as motor sequence learning in pursuit of a goal.

During the learning process, however, Kohler's chimps and the other animals seldom if ever performed the steps toward eventual success in a disordered manner. For instance, a chimp did not fail to grasp a banana, yet still bring its hand to its mouth and begin chewing. Though it may seem surprising that we would even comment on this, in our extensive experience with *rat* motor skill and motor sequence learning (Hermer-Vazquez, 2008; Hermer-Vazquez et al., 2004, 2007a,b), we have often seen the animals perform such movements strangely out of order—indeed, including failing to grasp a pellet during a reaching task and yet bringing their reaching paw to their mouths, sometimes with subsequent chewing. Gharbawie, Whishaw and colleagues (Gharbawie et al., 2007; Gharbawie and Whishaw, 2006) have noticed some of the same tendencies of rats learning the same skilled reaching maneuver both *before* and after cortical injuries.

In contrast, when non-human primates are learning a new motor skill, they appear to do so by concatenating simpler movements – such as extending the forearm, defending the face with the hand, grasping an object, or bringing the hand to the mouth while holding an object – in the correct order from the start (Rizzolatti and Luppino, 2001). These sub-movements are often referred to as movement primitives and have been studied extensively at the behavioral and neural levels (Cooke and Graziano, 2003; Graziano, 2006; Graziano et al., 2002a,b; Stepniewska et al., 2005). At the beginning of both ecologically relevant and, to some degree, arbitrary motor sequence learning, adult monkeys, chimpanzees and humans perform the new, more complex movements in a hesitant fashion, but almost always with correct ordering. Furthermore, they rapidly come to link the primitives or arbitrary steps into a whole, longer and more complex skill (Averbeck and Lee, 2007; Averbeck et al., 2006; Barone and Joseph, 1989; Hodgson et al., 2000; Ninokura et al., 2004; Shima et al., 1996). Similarly, from the time of reaching onset (~5 months) human infants have been shown to efficiently coordinate proprioceptive, visual and motor information into relatively smooth and correctly ordered sequences of steps to grasp visually detected objects, in both ecologically valid and more arbitrary and laboratory-set tasks (e.g. Barrett et al., 2008; McCarty et al., 2001). Obviously, however, humans and other primate species tested in the highly arbitrary tasks required some degree of trial-and-error learning (e.g. Averbeck and Lee, 2007; Averbeck et al., 2006; Hikosaka et al., 1999; Rand et al., 2000).

It has not yet been shown that rats possess movement primitives similar to those of primates (whether learned, innately encoded, or a combination of both), although there is some suggestion of it from studies of rats' food handling (Ivanco et al., 1996). Nor has it been demonstrated quantitatively that their learning in other-wise well-studied reach-to-grasp-food task (Gonzalez et al., 2004; Hermer-Vazquez, 2008; Hermer-Vazquez et al., 2004, 2007a,b; Hyland, 1998; Jarratt and Hyland, 1999; Kleim et al., 1998, 2002; Whishaw et al., 2003; Whishaw and Pellis, 1990), or any other type of motor skill, proceeds from sequences of disordered movement primitives to a correctly ordered and smoothened sequence. In primate studies cited above, the more ecologically valid a task appears to be, the more a correct ordering of movement steps is present from initial task learning. In the two experiments we present here, a group of rats performed the reach-to-grasp-food task that is considered to be at least semi-natural: for instance, it has been shown that rats use their forepaws to reach for food of the size used here, and can reach through slots or onto shelves to do so (Whishaw et al., 1992). In Experiment 1, we quantitatively and qualitatively analyzed rats' learning of the skilled reaching task in detail. In Experiment 2, we compared the sequence ordering during skilled task learning to that of a second group of rats learning an arbitrary, experimenter-determined sequence of movements. Our findings indicate that rats appear to possess at least some of primates' movement primitives, and that their learning of the (at least partly) ecologically valid skilled reaching task proceeds from certain types of disordered sub-movement sequences to a correctly ordered sequence. We also found that their learning of the correct ordering occurs at a rate

similar to that of animals in the arbitrary-sequence task, suggesting that rats, unlike primates, must learn to concatenate movement primitives in a logical and successful order.

2. Materials and methods

2.1. Subjects

We used 10 adult female Long-Evans rats, age ~4 months on arrival and weighing ~270–300 g. All housing conditions and procedures were approved in advance by the university's Institutional Animal Care and Use Committee (IACUC). The rats were housed in pairs in a reversed light-cycle, 12:12 h dark/light room in the department's animal facility. Before starting the experiments, we restricted the rats' food intake, gradually reducing their body weight to 85–90% of their ad libitum weights. During this time (~2 weeks), we handled them for approximately 10min/day. After the rats attained a stable, food-restricted weight, they were randomly assigned to either the skilled movement group, to be used in Experiments 1 and 2, or the arbitrary-sequence group, whose motor sequence learning was compared to that of the skilled group in Experiment 2.

2.2. Apparatus

The testing apparatus for the skilled task was made of clear Plexiglas with dimensions of 13.1 cm wide × 40 cm deep × 45 cm high (as in Whishaw and Pellis, 1990 and Hermer-Vazquez, 2008; Hermer-Vazquez et al., 2004, 2007a,b). The box stood on a plastic table with clean paper towels covering the floor for each rat. The front wall of the box had a slot 10 cm high and 1.2 cm wide through which the rats could reach for a food pellet. The shelf on which the food pellet rested had two small wells 1.3 cm beyond the slot, where the food pellets were placed, just beyond the reach of most rats' nostrils and tongues. The real pellets used for the GO trials in both experiments were banana-flavored and 45 mg and 4.2 mm in diameter (Bioserv Inc., Frenchtown, NJ). The artificial, plastic-scented beads used on control, NO-GO trials, to determine whether rats' reaching was olfactory guided, were 4.1 mm in diameter and virtually visually identical to the food pellets. (These same beads were used in a study of the sensory guidance of rats performing the skilled task used here; Hermer-Vazquez et al., 2007a,b.)

For the control, arbitrary-sequence task, a standard MedAssociates rat operant chamber (MedAssociates, St. Albans, VT) was used, which contained a house light, olfactometer, nose port, lever, and a pellet magazine. On each trial, the rats in this group sniffed either a GO or a NO-GO odor inside a standard rat nosepoke hole, and on GO trials were to press a lever approximately 7.6 cm to the rat's right. Programs for the training stages and final control task were written in standard Med-PC programming language.

2.3. Video recording and analysis

The animals were videotaped using a Super VHS video camera (Panasonic, USA) at 30 frames/s. Rats that were comfortable performing the task in regular room lighting were videorecorded with the lights on, whereas more anxious rats were tested under low-luminance red lighting. Recordings were coded using a motion-analysis VCR and with a coach's remote (Lafayette Instruments, Lafayette, IN). The field-by-field display function of this VCR allowed us to code the rats' movements at 17 ms resolution.

2.4. Procedure

2.4.1. Skilled motor task—This task was a discriminant responding procedure, with odor-guided GO and NO-GO trials. At the beginning of training, each rat was placed in the box and given time to discover that several pellets were resting on the shelf beyond them. They were allowed to reach for a food pellet with their limb of preference. Once they sufficiently displayed

their handedness, pellets were placed in the well contralateral to their reaching paw and videotaping began. Pellets were replaced when the rat retrieved and consumed the food or displayed an unsuccessful reach, immediately after which the pellet was pushed away or removed. Daily sessions concluded when the rat lost motivation and no longer attempted to reach (usually after 50–100 motivated trials). On approximately 15% of trials, an artificial plastic bead was placed in the contralateral pellet well, or with the real food pellet placed in the ipsilateral well or between the two wells but farther away from the rat, to keep the initial sniffing phase necessary (because the pre-reaching sniffs are used to determine the endpoint of the reaching trajectory Hermer-Vazquez et al., 2007a,b). Training ended with 3 days of level performance, defined as an asymptote in the percent of correct reaches (on which the percentage of correctly ordered reaching sequences did not differ by more than 5% of the running asymptotic mean). Additionally, following the last day of training, each rat was tested for 20 trials with a plastic, visually similar bead in order to confirm that the reach was olfactory guided. The video recordings of each rat were later analyzed and scored based on their sequence of movements to retrieve a pellet.

2.4.2. Arbitrary-sequence task—This task was also an odor-guided discriminant responding task, but it differed fundamentally from the skilled task in that it consisted of a sequence of arbitrarily ordered actions rather than a series of movement primitives organized in a more natural manner. Each rat was placed into a MED-PC chamber and 4 days per week was trained in progressive components of the task using the MED-PC computer programs. In early training, the rat learned how to retrieve a pellet from a pellet dispenser, then learned to press the lever, and finally learned to respond to a house light and associate the house light with a nose poke where an odor is released. After this training, which took most animals 4 days to complete, these steps were all linked in a final task in which the rat poked its nose to detect an odor following the illumination of the house light, and pressed the lever to acquire a food pellet. Rats were shaped to use the same paw for lever pressing, similar to the skilled rats. They were tested for 70 trials each day, which was the average number of trials per day for the skilled group. Training concluded when they reached an asymptote of percent correct reaches for 3 days. All data was stored in the computer and transferred to an Excel spreadsheet to determine the daily percent correct. The stages were videotaped so that they could also be coded and analyzed. As with the skilled group, on test trials the arbitrary-sequence rats were given ~15% of trials in the MED-PC chamber with a NO-GO odor to be sure their lever press was determined by the GO odor. Also as with the skilled group, rats in the arbitrary-sequence task mostly avoided an arm movement after the NO-GO odor.

2.4.3. Video coding

2.4.3.1. Skilled task: The rats' movements were analyzed based on the sequential order of putative rat movement primitives comprising a successful skilled reach (correctly ordered and recorded as 1–8). The rat reaching-related movement primitives were defined as follows: (1) sniffing the olfactory cue, (2) shifting the weight to the non-reaching fore- and hindpaws, (3) lifting the correct reaching paw, (4) extending the reaching paw, (5) grasping the target food pellet, (6) retracting paw while holding the pellet, (7) placing the pellet in the mouth, and finally, (8) chewing the pellet. Additional codes were included for out-of-sequence movements including lifting the wrong paw or both paws (0^-), pushing the pellet away (0^+), or performing the remainder of the reach after reaching quickly two or more times in a row (4^*). Any other anomalies were recorded with a description. Table 1 below gives an example of the coding of two trials, both of which were incorrect.

2.4.3.2. Arbitrary-sequence task: Analysis of movement was based on performance of an arbitrary sequence of moves that were to be compared to learning the sequence of steps in the skilled motor task. Each trial was coded based on the following, experimenter-determined

sequence (correctly ordered as 1–5): (1) nose poking with odor release, (2) shifting the weight to the non-reaching paws, (3) lifting the stereotypic paw used for lever pressing, (4) pressing the lever with the stereotypic forepaw, and (5) retrieving pellet. After determining the consistent lever pressing behavior for each rat, pressing the lever with the opposite paw or both paws was coded as 0⁺ instead of 3. The arbitrary-sequence task actually had eight stages, but we did not code the last three for this task, unlike the skilled task. Thus for our task comparisons we used only five stages, and we reserved our detailed analysis of the last three stages for the skilled task only. An example of the coding of two trials is shown in Table 2.

2.4.4. Statistical analyses—All analyses were performed with the Statistica software package (StatSoft, Tulsa, OK), and all analyses below were planned contrasts, once we knew the number of testing days each rat required to reach asymptote. For Experiment 1, involving only the skilled-task rats, we first tested whether there were main effects of RAT or testing DAY, using the percentage of correctly ordered sequences (*% correctly ordered*) as the dependent variable, which was the case for all analyses below unless noted otherwise. To analyze the possible effect of DAY, we aligned all rats by their three final, asymptotic days and performed an ANOVA on the *% correctly ordered* across days (9). The skilled rats' dramatically different number of days to asymptote (from 4 to 9 days) posed a problem for further analyses, however, because this difference created a large and possibly unnecessary amount of variance. We therefore next categorized rats by LEARNING RATE (2: slow versus fast), taking a median split of the number of days to asymptote, and performed two further analyses: a test for an effect of LEARNING RATE and a LEARNING RATE (2) × DAY (9) ANOVA, starting from Day 1. To analyze whether the skilled task's last three phases (grasping the pellet, bringing the reaching paw to the mouth, and placing the pellet in the mouth and chewing) may consist of a single movement primitive, as suggested by some reports with primates (Graziano and Aflalo, 2007; Martin et al., 1999; Yao et al., 2002), we analyzed whether there was an effect of DAY for correctly ordering these sequences across the last 5 days of testing, which was as far back in the total number of days we could go while retaining at least three data points for each day (see Fig. 3 in Section 3). Finally, we performed a detailed analysis of the patterns of errors and learning across all testing days, by sorting each reaching trial's sequence of sub-movements to find the most common patterns, calculating how often they occurred out of the total number of trials, and then noting the stereotypic phases of progression.

For Experiment 2, in which we compared learning of the skilled and arbitrary-sequence tasks, we first checked for main effects of RAT (10) and testing DAY (again 9, the maximum number of days required by some rats in each group). In order for the comparison of the two tasks, despite their many differences, to be valid *for our purposes*, we performed three ANOVAs to determine whether the tasks were similarly difficult: one to compare the groups' number of days to asymptote, another to compare the asymptotic performance of rats in the two groups, and a final analysis to determine whether there were any differences between the groups across testing days. Finally, because rats in the arbitrary-sequence group also took from 4 to 9 days to complete the task, we checked for a significant interaction among GROUP (2), LEARNING RATE (2), and DAY (9). Because this was the interaction we wanted to examine, we did not check for main effects or for interactions between any two of the three factors. This is because the vertex-to-vertex slope for an interaction can still be significantly different from 0 even if there are no lower-order significant effects, making a significant interaction linearly independent from the lower-order slopes.

3. Results

3.1. Experiment 1: analyses of learning to correctly order the skilled task movement sequence

Rats in the skilled task group took from 4 to 9 days to attain asymptotic performance across 3 days. We first examined whether rats in this group differed in their % of correctly ordered sequences, collapsing across testing days, finding that they did not (Fig. 1a; $F(5, 26) = 1.442$, $p > .24$). We next checked for a difference in the % *correctly ordered* across testing days. Although we expected to find a significant improvement across testing days, given that the Day 1 average was just over 30% and the asymptotic levels were above 70%, the substantial variance caused by rats' dramatically different number of days to asymptote created only a marginal effect (Fig. 1b; $F(8, 23) = 2.0547$, $p = .08453$). We therefore divided rats into fast learners and slow learners, using a median split of the days to complete the task (fast: 4–6 days; slow: 7–9 days), and found that collapsing across testing days, the fast learners had a higher % *correctly ordered* (Fig. 2a; $F(1, 30) = 4.2001$, $p = .0495$). They also showed different learning profiles across testing days: although fast and slow rats performed roughly equally on their first testing day (Fig. 2b), they immediately improved to over 70% correct. In contrast, slow learners improved more gradually before a final, less substantial “jump” to >70% correct ($F(4, 18) = 4.346$, $p = .01237$). Finally, we analyzed the % *correctly ordered* for the last three phases of the task, which could attain values higher than the percentage for completely correct sequences. We used data from only the last five testing days so that there would be at least three data points for each day. With this analysis, we found that the skilled-task rats indeed improved across the course of testing days, with relatively little variation (Fig. 3; $F(4, 8) = 16.417$, $p = .00063$). This finding suggests that rats learn to correctly order these three phases, implying that they may not comprise, together, a single movement primitive.

3.2. Experiment 1: analysis of stereotypical patterns of failure on reaching trials

We examined the skilled rats' common error types using the database of 2129 coded reaches for the six animals and further video analysis. Out of the total of 2129 reaching trials, 1001 (47%) were error trials, many of which included disorganized reaching components. Table 3 lists the most common error patterns and their rate of occurrence. One of the most common errors early in the learning process was reaching without sniffing first, which usually resulted in an inaccurate trajectory that missed the pellet by 1–2 mm or more. (We had previously found that the initial sniffs of the pellet were necessary to locate the target precisely in space Hermer-Vazquez et al., 2007a,b.) Often on such reaching attempts, the rats would either bring their empty forepaw to their mouth and begin chewing, or would initiate a second reach with the same reaching paw (4*) or the wrong paw or both paws (0⁻). They also commonly chewed after failing to grasp the pellet, retracting the paw nonetheless, then dropping the arm without attempting to bring the hand to the mouth. In general, chewing after a missed reach of any type occurred frequently, both early and late in testing. Two other signs of disorganization during learning were bringing the paw to the mouth without holding a pellet (without chewing), and releasing the pellet either as the forepaw was being retracted or brought to the mouth. The most common error types, besides reaching without sniffing or chewing at inappropriate times, were missing the pellet on the first attempt, or dropping the pellet while retracting the reaching paw toward the mouth.

3.3. Experiment 1: common learning patterns

Although we found many variations on common learning patterns, we will summarize the main progression patterns here. Initially, most rats used their tongues in trying to obtain the food pellet, but because the pellets were just out of almost all rats' tongues' reach (13 mm beyond the slot), they quickly extinguished this behavior—usually in the first two to five attempts. As they began to learn to reach for the pellet, it typically took them several trials (usually 5–20)

to learn to extend their forepaw far enough to contact the pellet. After reaching this point, however, their reaches were erratically located for as many as 50–100 more trials, because the animals were not sniffing the pellet to locate it in space. Even after learning to sniff and reach correctly, some animals continued to reach without sniffing, despite the occurrence on ~15–20% of trials of a probe in which the pellet's location differed, or the pellet was a plastic but visually identical dummy. Although most animals had considerable trouble learning to sniff consistently before reaching, a small number appeared to sniff the pellet and reach to the correct location almost immediately.

Animals committed many errors of disorganization as their skill learning progressed, such as the aforementioned example of continuing to reach without sniffing first, even after having had success (obtaining and consuming the pellet) using the correct sequence. More striking errors of disorganization, and ones that often continued as animals neared asymptotic performance, included chewing or even placing the paw into the mouth and chewing—without any pellet! Some animals also brought their paw to their mouth without grasping a pellet, but did not chew. It took most rats at least 2 days of ~70 trials each (after whatever initial problems they had) to use the presence or absence of a somatosensory stimulus in their palm to determine whether they should continue their reaching trajectory. Alternatively, they may have learned to use olfactory information, but current evidence indicates that for rats, the reach-to-grasp-food task requires olfaction for target location and tactile information for grasping and holding the pellet (and not vision; Whishaw and Tomie, 1989).

Once the skilled-task rats had overcome the above difficulties, their reaches consisted of the following steps: (1) sniffing to determine the pellet's location, (2) shifting the bodyweight to the non-reaching paws, (3) lifting the correct paw and maneuvering it through the slot so that the paw contacted the shelf lightly as it progressed toward the pellet location, and then (4) using the presence or absence of a pellet in their grasp to determine whether to continue the task maneuver. At this point their errors usually involved making inaccurate reaches despite sniffing first. On some occasions, they would mistarget the pellet and inhibit making further attempts, especially since the experimenter had been swatting away the pellet after their first try to condition against double- or triple-reaching. Other times, however, the rats would reach again with the same paw, almost always without sniffing first, or would alternate paws in a frenzy of mistargeted reaching. Rats that learned the task quickly ($N=3$ out of 6) and attained a high % *correctly ordered* generally reached only once if they missed, that is, performing the correct sequence whether they missed or succeeded.

3.4. Experiment 2: comparison of learning to correctly order movement sequences as a function of experimental task group

In this experiment we tested the hypothesis, stemming from our preliminary observations and from the results of Experiment 1, that initially the skilled-reach movement steps would be to some degree arbitrarily or randomly ordered. To do so we compared the skilled rats' progression, in terms of % *correctly ordered*, with that of rats in the arbitrary-sequence task. Remarkably, as with the skilled task, rats in the arbitrary-sequence group took 4–9 days to complete 3 days of asymptotic performance. Our first analyses centered on determining whether certain factors such as RAT needed to be included in the remaining analyses, and on comparing the difficulty of the two tasks. This latter concern was important, because if the two tasks were not similarly difficult, it would immediately invalidate further comparisons that were closer to the main purpose of Experiment 2.

With the dependent variable of % *correctly ordered*, there was only a marginal RAT difference among the 10 animals from the combined groups (Fig. 4a; $F(9, 46) = 1.6321$, $p = .13428$). It can be seen in the figure that the first six rats, who were in the skilled group, exhibited similar variations in the overall percentage of correctly ordered sequences, compared with those of the

last four, arbitrary-group rats. We also tested for an increase in performance across testing days, combining the two groups. Possibly because the two groups improved in a similar manner, with the arbitrary-sequence group thus reducing the overall variation, we found a significant effect of testing day (Fig. 4b; $F(8, 38) = 2.7195, p = .01789$). Providing stronger evidence for this possibility, the groups did not differ in their average % *correctly ordered* (Fig. 5a; $F(1, 38) = .01376, p = .90723$), nor did they differ in their average number of days to reach asymptote (Fig. 5b; $F(1, 8) = .256, p = .62653$).

With evidence that the two tasks were similarly difficult, we performed two final group comparisons. The first was to evaluate the day-by-day progression of learning in skilled- versus arbitrary-sequence rats. This analysis yielded striking evidence animals in each group acquired the correct ordering of their tasks at a similar rate across testing days, which can be seen in the nearly identical progression of the two groups in Fig. 6 ($F(8, 38) = .13216, p = .99734$). The results displayed in Fig. 6 also further support the argument that the two tasks were of similar difficulty, especially since the groups asymptoted at nearly identical levels. Last, we divided the arbitrary-sequence group into slow and fast learners, using the same median split as with the skilled-task animals, and performed the planned analysis of slow versus fast learners in each group across testing days. Although the slowly learning arbitrary-sequence group initially performed at a lower % *correctly ordered* than did the skilled animals, the slow and fast subgroups within the skilled and arbitrary groups otherwise displayed strikingly similar learning trajectories, at least in terms of the overall percentage of correctly ordered sequences (Fig. 7).

4. Discussion

In this study, we found that in the skilled reaching task rats progressively learned to organize their reaching sequences correctly, and that their intermediate-level task performance consisted of multiple types of disorganized movement sequences. Although skilled rats exhibited many variations in their disorganized performance, some errors were more common than others. The most common errors of disorganization involved moving the empty forepaw toward the mouth, and chewing when there was no pellet in the mouth. Slow learners and rats that asymptoted at a relatively low level continued to make such errors, in some cases even after 6–9 days of training. We compared slow and fast learners in the skilled group to those in the arbitrary-sequence group, and found nearly identical patterns of learning to perform the tasks with correctly organized sub-movements. The two tasks were not comparable in many ways, especially in that each experimenter-determined step in the arbitrary task did not stem logically from the prior step, nor did each step flow logically or ecologically validly into the next. This fact, however, permitted us to test the hypothesis that rats in the skilled task, *like* primates in tasks with arbitrary sequences but *unlike* primates in more ecologically relevant tasks, proceeded from substantial disorder to relative order in their sequence performance. Overall, our results suggest that for rats, learning the reach-to-grasp-food task involves learning to sequence putative movement primitives in the correct order.

4.1. Randomness in early and intermediate performance of the skilled task

When humans or monkeys are learning a similar reach-to-grasp food task, they nearly always perform the sub-movements in the correct sequence (Castiello, 1996; Whishaw, 2003; Whishaw et al., 1992a,b). In contrast, our experiments revealed substantial disorder in rats' performance of the skilled task, particularly during early-and intermediate-stage learning. Their improvement in the measure % *correctly ordered* remarkably resembled that of rats learning the sequence of arbitrary movements. Common errors of disorganization in the skilled task included reaching without sniffing first to determine the food pellet's presence and location (Hermer-Vazquez et al., 2007a,b), and more surprisingly, bringing their empty reaching

forepaw to their mouth, and chewing without a pellet in the mouth—often without even attempting to bring the paw toward the face. Each of the two groups tested here (the skilled and arbitrary-sequence groups) contained slow and fast learners, with slow rats in each group taking 7–9 days to fully asymptote and fast rats taking 4–6 days. Our comparison of slow and fast rats across the skilled and arbitrary-sequence groups revealed even more strikingly similar learning patterns, at least in terms of % *correctly ordered* across testing days. While this does not necessarily mean that rats in the two groups displayed similar *kinds* of disorder, at the very least it indicates that the skilled rats exhibited disorganized sequencing not seen in humans or monkeys learning a similar task.

In terms of correct ordering during early and intermediate learning, and to some extent, even during asymptotic performance, rats in the skilled group resembled monkeys and humans learning *arbitrary-sequence tasks*. In one example, Averbek et al. trained monkeys to produce sequences of gaze shifts, presented in blocks, with performance of a different sequence being required after several trials with the previous sequence. The animals' learning progressed with subsets of patterns from previous blocks being most easily produced in subsequent blocks (Averbek et al., 2006). Although the monkeys' percentage of correctly ordered sequences was initially low in each block, the learning process was straightforward in that the animals made use of previously learned patterns. In this sense Averbek's monkeys differed from the skilled rats tested here, which had to learn to use sensory cues to "know" a pellet was in their forepaw even though they often grasp food objects in the wild and the laboratory (when pellet-sized food is given). In another example, Toni et al. presented human subjects with a sequence of 18 abstract object pictures, each of which arbitrarily signaled the subjects to press one of four keys on a keypad (Toni et al., 2001). Unknown to subjects, the pictures were flashed in a variety of ordered sequences. There was a random component added to the time interval between image presentations to reduce one pattern cueing the motor preparation for the next movement. Subjects learned the associations by trial-and-error and exhibited substantial disorder, with their average initial ordering at only ~55% correct. After several sessions, however, they performed the sequences in the correct order >95% of the time. In contrast, the same subjects performed a control task with more directly cued key presses at close to 100% correct from the start. Although serial reaction time tasks such as Toni et al.'s resemble our and Averbek et al.'s motor sequence tasks less, somewhat similar results can be seen when performed in humans, monkeys and rats. In these tasks, the disorder-to-order learning process is typically seen in terms of the response time to each stimulus, with dramatically longer response latencies before the procedural sequence is fully learned (Bari et al., 2008; Koch and Hoffmann, 2000; Nissen, 1987; Procyk et al., 2000; Sohn and Lee, 2007; Willingham et al., 1989).

However, in many cases humans and monkeys have performed surprisingly well on even very arbitrary sequential movement tasks. For example, Tanji and Shima trained macaques to learn four different sequences of three movements that consisted of pushing, pulling or turning a manipulandum. After being given only five learning trials for each sequence, a tone indicated that the animals should perform the current sequence. Subjects were then given blocks of test trials for each sequence. Impressively, all animals performed above 95% correct (Shima and Tanji, 1998; Tanji and Shima, 1994). These and similar results indicate that for relatively short sequences of arbitrarily ordered movements, primates acquire the task knowledge rapidly—almost as well as they perform smoothly concatenated movements for more ecologically relevant tasks such as reaching to grasp and eat food. In striking contrast, even though skilled-task rats were given repeated blocks requiring the identical sequence, their learning process was characterized not only by trial-and-error (e.g. as with Kohler's chimpanzees), but also by the production of substantial random and seemingly bizarre orderings of their sub-movements.

4.2. Rats and movement primitives

There is increasing evidence that macaques and possibly dogs (Fritz and Hitzig, cited below) use cortically encoded “movement primitives” – such as reaching, grasping an object, holding the object, bringing the hand to the mouth, or using their hand to cover their face in self-defense – for many of their goal-oriented actions (Cooke and Graziano, 2003; Fritz, 1870; Graziano, 2006; Graziano et al., 2002a,b; Rizzolatti and Luppino, 2001; Stepniewska et al., 2005). These movement primitives and their cortical organization have been studied electrophysiologically as well as behaviorally. Microstimulation of various sub-regions of primate cortical motor areas has revealed that if relatively long stimulus trains are used (~300–500 ms), whole sub-movements including those listed above are evoked. At the present time, there appears to be no similar research in rodents, except for (1) descriptions of the visually evident (i.e. kinematic) phases of natural movement sequences (e.g. Whishaw and Pellis, 1990), such as reaching to grasp food or catching insect prey (Ivanco et al., 1996) and (2) cortical microstimulation studies with much shorter pulse trains (e.g. Giuffrida et al., 1985; Neafsey and Sievert, 1982). Interestingly, even with brief microstimulation pulse trains in rats, “complex” movements such as combined forepaw and hindpaw motions have recently been observed (Molina-Luna et al., 2007).

Our study of rats’ disorganized movement sequences, however, allows us to begin to evaluate behaviorally whether they may have reaching-, grasping- or eating-related movement primitives similar to those discovered in non-human primates. First, rats are known to locate nearby food with olfaction much more than with vision (Hermer-Vazquez et al., 2007a,b; Whishaw and Tomie, 1989). In the current experiment, their failure to sniff before reaching during early skilled-task learning suggests that the olfactory determination of reaching location and the subsequent extension of the forepaw may be separately encoded sub-movements. Second, forepaw extension often occurred during early learning without sniffing, grasping, or retracting the paw toward the mouth, suggesting that it too may be a movement primitive. Third, grasping does not happen during early learning; rather, if rats contact the target, they usually make a raking motion to try to draw the pellet closer to their mouths, with or without eventually grasping it (Whishaw and Pellis, 1990). Moreover, retracting the paw toward the mouth often occurred, especially during intermediate-stage learning, without having grasped or raked the pellet, and without any follow-through such as moving the forepaw into the mouth. These two points suggest that as with primates, grasping the food object and retracting the forepaw may also be movement primitives, as may be the case in rats for raking food toward the mouth (which to our knowledge is unknown as a movement primitive in primates). Finally, chewing occurred often without placing the forepaw into the mouth or even after failing to retract the paw off the shelf, providing clear evidence that chewing is a possible movement primitive that is separate from the motions of getting the food into the mouth. We therefore believe that our study provides the first evidence of primate-like movement primitives in rats. Furthermore, rats’ learning of the reaching task appears to consist of learning to order these movement primitives into a correct sequence.

There are alternative interpretations of our data, which we hope will be examined in further studies. For instance, it is possible that rats do not so much learn to concatenate primate-like movement primitives into the correct sequence, but rather, learn to inhibit natural tendencies (such as initially seeking to “grasp” the food pellet with their tongues) and then, partly by trial-and-error, discover which non-prepotent, other primitives are more likely to bring success in the tasks we used. It is also possible that the kinematically defined reaching steps identified by Whishaw and colleagues are in fact the “real” movement primitives. Though we cannot rule out these alternatives with our present data, we nonetheless prefer our initial interpretation, primarily because of the strong evidence in this study that rats have actual primate-like

movement primitives. However, we say this with further caveats in mind, which we discuss below.

4.3. Neural, comparative and evolutionary perspectives on whether rats have movement primitives and the mechanisms to temporally sequence ecologically relevant sub-movements

Our hypothesizing that rats have movement primitives that at least somewhat resemble those found in macaques (and possibly dogs, Fritz, 1870) begs the question of whether rats have the primate-like motor cortical cell aggregations that are known to be critical for production of movement primitives in species of that order. It further begs the issue of whether rats have the temporal sequencing mechanisms known to exist in the primate brain for linking “natural” or ecologically relevant movements. We discuss each of these issues in turn below.

Regarding whether rats have the cortical motor areas and sub-fields within them for movement primitives, in primates reaching- and grasping-related sub-movements are mainly represented within the ventral premotor cortex, also known as F5. There is some general evidence for the similarity of rat and primate motor cortical areas (Neafsey et al., 1986; Wise, 1985). Although rats clearly have a rostral premotor cortex (e.g. Reep et al., 1987), it is somewhat unresolved whether they have a ventral premotor cortex, or F5 (Li et al., 1990; Rouiller et al., 1993), where again, many hand-related movement primitives are encoded in primates (Rizzolatti and Luppino, 2001). For instance, some anatomical evidence points to rats having a mixture of ventral premotor and supplementary motor cortices (Rouiller et al., 1993). Furthermore, there appears to be little evidence that microstimulation of the rat ventral premotor-like area has produced our putative movement primitives, partly because, to our knowledge, mainly research with short-duration current trains (e.g. 20 ms rather than the 300–500 ms needed for movement primitive production in macaques) has been performed thus far (as in, e.g. Neafsey et al., 1986; Neafsey and Sievert, 1982). At least two possibilities for rats’ having neural representations of our behaviorally indicated movement primitives exist. First, the less distinctly organized rat ventral premotor area, if electrically stimulated as in primate experiments, may be revealed to have cell aggregations that are a critical component of a cross-area network that activates the movement primitives. Second, representations of these sub-movements might exist elsewhere in the rat’s brain. It is also possible, of course, that whole movement primitives are not represented anywhere in the rat brain, but this seems unlikely given our observation that apparently whole sub-movements, although often disorganized in their temporal order, were present from the beginning of skilled task learning.

Regarding the issue of whether rats have the neural circuitry to link ecological movements together, two macaque motor areas and their possible rat homologues are of interest. The first is the supplementary motor area (SMA), mentioned earlier, and the second is the pre-supplementary motor area (pre-SMA). In primates these two areas have been found critical for correct movement sequencing (Shima and Tanji, 2000). The SMA has been found to be more involved in the motoric aspects of smoothly linking a series of sub-movements, appearing to come to represent their relational order as training progresses. It also has many neurons whose firing rate increases during performance of movement primitives (like many F5 neurons) or during arbitrary sub-movements (such as pushing or pulling a manipulandum). The pre-SMA, on the other hand, has been found to represent the more abstract ordinal position of each sub-movement within a larger sequence of N moves (Shima and Tanji, 2000).

We performed multiple literature searches, all of which yielded no anatomical or functional evidence that rats have a pre-SMA that is homologous to that in primates. This finding suggests that over the course of repeating a movement sequence many times, rats may never develop abstract knowledge of the ordinal positions of the movements. However, as discussed earlier, they do appear to have an SMA that may be intermixed with the ventral premotor cortex. And

clearly in both our tasks, the rats came to correctly link their movements together, developing increasing smoothness and speed as they did so. This suggests that either in an evolving SMA or else-where neurally, they have the kind of circuitry needed for learning to smoothly concatenate movements in specific (and reinforced) order. However, the work of Shima and Tanji (2000) suggests that rats may not develop abstract knowledge of ordinal position, or perhaps of an abstract categorization of the sequence they have learned, in contrast to macaques.

Rats also differ from nearly all primates in that, though they have better vision than usually acknowledged (Prusky et al., 2000), they rely primarily on olfaction for determining their reaching trajectories (Hermer-Vazquez et al., 2007a,b; Whishaw, 2003; Whishaw and Tomie, 1989). This probably explains why they do not automatically adjust their grasping position as they move their forepaw toward an object of a given size, shape and orientation (Metz and Whishaw, 2000). In contrast, even human infants who have just attained reaching age adjust their grasping position as they move toward an object, taking into account the object's shape, size and orientation (Barrett et al., 2008; McCarty et al., 2001). This behavioral difference suggests a profound difference in the organization of cortical circuitry involved in reaching-related movements between rodents and primates: the main cortical input to F5 and other areas involved in activating and executing primate movement primitives is a visual area critical for representing the shapes of objects, the anterior inferotemporal cortex (e.g. Borra et al., 2008; Raos et al., 2006). At the behavioral level, this difference most likely increases the time and effort rodents must expend in learning to organize and smoothly perform a movement sequence, and may add a degree of randomness not seen in primates as they learn. Rats possess stereo-olfaction (Rajan et al., 2006) and therefore can localize nearby objects in space if the objects have a detectable odor. This makes some of their sequence disorganization during skilled task learning all the more surprising, e.g. by not regularly sniffing to determine target location before reaching, and chewing even though the odor of the chocolate or banana pellet has not been detected near the mouth. Certain aspects of the task that are so easy for primates, such as using somatosensation (or for rats, olfaction) to know that the target is in their palm, must be learned over many trials by rats. We suggest that for rats, several aspects of learning the skilled and ecologically relevant reaching task resemble arbitrary motor sequence learning, with certain forms of disorder occurring despite their regular use in daily life.

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Fig. 1.

Results of analyses checking for main effects of RAT and DAY among the skilled group. (a) Although skilled rats 5 and 6 appeared to perform better than rats 1–4, there was so much variability in rats' performance that they did not differ significantly from one another. (b) We expected a main effect of DAY given that the rats overall started in the ~35% range but asymptoted above 70%. However, the rats' variation, lining them up by their three asymptotic days, prevented finding a significant improvement across testing days. See Fig. 2a and b for a significant difference and an answer to why it was not found here.

Fig. 2.

Fast versus slow learners in the skilled group. (a) In overall % *correctly ordered*, fast learners outperformed slow learners. (b) Fast learners differed clearly, in terms of % *correctly ordered* across testing days as well as days to criterion, from slow learners.

Fig. 3. Skilled-group rats improved in their ordering of the last three task phases (bringing the pellet to the mouth, placing it inside and chewing) across testing days.

Fig. 4. Testing for main effects of RAT and testing DAY across the skilled and arbitrary-sequence groups. (a) Rats in the combined group did not differ significantly from one another. (b) However, with the two groups combined, a clear improvement across testing DAY emerged.

Fig. 5.
The skilled and arbitrary-sequence groups did not differ from each other in terms of average % correctly ordered (a) or days to criterion (b).

Fig. 6. Across testing days, rats in the skilled and arbitrary-sequence groups displayed a remarkably similar improvement in their percentage of correctly ordered movements.

Fig. 7. Slowly versus quickly learning rats in each of the two experimental groups (skilled and arbitrary sequence) exhibited strikingly similar patterns of improvement across testing days.

The coding of two skilled task trials on which the rat failed to obtain the target pellet. On the first trial, the rat extends the correct reaching paw but does not grasp the pellet; then, with its arm still extended, the rat begins chewing as if the pellet was in its mouth. On the second trial, the rat extends the correct reaching paw but fails to grasp the pellet (note the missing stage 5). It then retracts its hand and knocks the pellet out of reach.

Table 1

Trial	M1	M2	M3	M4	M5	M6	M7	M8
1	1	2	3	4	8			
2	1	2	3	4	6	4	0 ⁺	

Table 2
The coding of two trials of the arbitrary-sequence task. On the first trial, the rat performs the sequence correctly except that it fails to nosepoke before pressing the lever. On the second trial, the rat starts correctly but then lifts and presses the lever with the wrong reaching paw.

Trial	M1	M2	M3	M4	M5
1	2	3	4		
2	1	2	0 ⁻	4	

Table 3

Frequency of common errors or error sequences on skilled reaching task trials. All listed patterns are mutually exclusive with one another.

Error sequence	% of total error trials
Dropping pellet after grasping it on the first attempt, while retracting paw or bringing pellet to mouth	6%
Bringing paw to the mouth without pellet, or dropping the pellet while retracting paw and still continuing to lift paw toward mouth	3%
Reaching correctly without sniffing first	<1%
Reaching incorrectly without sniffing first, without continuing the reach (see below)	12%
Reaching incorrectly without sniffing first, then placing paw on shelf without grasping pellet, and chewing with paw remaining on shelf	4%
Reaching incorrectly without sniffing first, retracting paw but dropping arm before reaching mouth, and still chewing	4%
Reaching inaccurately without sniffing first, yet bringing the closed but empty fist to mouth and chewing	2%
After failure on the first attempt, double reaching with the same paw or with the opposite or both paws, without sniffing first	9%
Initially lifting wrong paw	1%
Other	5%
Total	47%