Acquisition and Automatization of a Complex Task: An Examination of Three-Ball Cascade Juggling

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ABSTRACT. The learning patterns of three-ball cascade juggling from acquisition until automaticity were examined in 10 participants. On the basis of outcome measures derived from 26 practice sessions and 4 periodic probe sessions, the authors differentiated participants into 3 distinct learning types: a proficient group, an emerging group, and a single late learner. The proficient group was distinguished by how rapidly they learned and automatized performance. Most interesting, an inverse response cost (i.e., performance boost) on the secondary task was found in the majority of proficient group members during the dual-task condition. The present results are discussed in relation to the P. L. Ackerman model (1987, 1988) of complex skill acquisition as is the significance of the inverse response cost finding.

Keywords: automaticity, juggling, learning, psychomotor skill

Juggling is a complex motor task, the execution of which has been documented across the millennia. Representations of skilled juggling have been found on the walls in the Pyramids of Egypt, and there are repeated literary references to juggling from early printed texts through to modern times, as can be seen in the following quotation from the Art of Juggling or Legerdemaine (Rid, 1612/1974).

The Art of Juggling

Remember that a jugler must set a good face upon that matter he goeth about, for a good grace and carriage is very requisite to make the art more authenticall.

Your feates and trickes must be nimbly, cleanly, and swiftly done, and conveyed so as the eyes of the beholders may not discern or perceive the tricks, for if you be a bungler, you both shame your selfe, and make the Art you goe about to be perceaved and knowne, and so bring it into discredit.

Juggling has moved from the more ethereal domain of sleight of hand and magic, as was considered to be the case in Samuel Rid’s time, to the more mundane realm of being viewed merely as a complex motor task. There are many forms of juggling, in part defined by the number of items being juggled, what is being juggled, and the method being used. The data presented here were derived from an investigation of three-ball cascade juggling, which is the easiest form of three-ball juggling: One hand throws a ball in an arc to the other hand in an alternating pattern so that one ball is airborne at all times and the hands trace a figure-eight pattern (described for the performer in Finnigan, 1992, and mathematically in Beek & Lewbel, 1995; Beek & van Santvoord, 1992; van Santvoord & Beek, 1996). The act of juggling three balls involves the complex coordination of a series of motor, cognitive, and perceptual activities. Those include throwing, catching, tracking, estimation of trajectories, and compensating for weight and size differences among the objects being juggled. All of those activities must become integrated and fully automatic if one is to become skilled at the task. The acquisition and automatization of three-ball cascade juggling, a complex motor skill, was the focus in this study.

Juggling itself has been studied in recent years, but often with a particular focus on its mathematical, mechanico-physical (e.g., robotics), kinesthetic, and perceptual components (e.g., Beek & Turvey, 1992) or as an example of a complex motor task that enables the investigator to uncover learning principles (e.g., Trussell, 1965). To date, however, no researcher has used the learning of juggling as a tool to investigate the automaticity of a complex motor skill.

Although there are numerous definitions of automaticity, we have adopted a working definition similar to that of

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Heuer (1996). He described it as "a modification of task performance in the course of practice such that interference with all other kinds of concurrent tasks will be reduced" (p. 144). The implication of that definition is that, with automatization, the attentional demands of the task have decreased to a point where the task is less effortful and sufficient processing resources remain for the person to perform a concurrent activity.

Ackerman (1987, 1988, 1990, 1992) has developed and empirically investigated an integrative theory of the factors associated with complex skill acquisition (usually, air traffic control simulation). His model incorporates concepts derived from Shiffrin and Schneider's (1977) theory of automatic and controlled processing and from his own theory of change in skill acquisition as a function of task characteristics (e.g., consistency of information-processing demands, task complexity, and degree of task practice). The integrated theory resulted in a three-stage model of skill acquisition (also see Anderson, 1982; Fitts & Posner, 1967). The first phase is the cognitive stage, in which large demands are placed on the learner in terms of understanding the instructions and formulating strategies, among other things. Once learners have acquired the basic procedures, they will move into the second phase. If the task contains inconsistent information-processing demands, however, the learner cannot proceed beyond the first stage. The second stage is the associative phase, which involves the proceduralizing of task strategies in a way that will enhance performance and reduce errors. The final stage is the autonomous phase, during which the task becomes automatic. At that point, the learner can complete the task with little attentional effort. The third stage is similar to other notions of automatization of performance.

Ackerman's three-stage theory was used as a framework for our present examination of the acquisition and automatization of three-ball cascade juggling. Development of juggling skill was examined at various points, from the initial acquisition of the skill toward eventual automatization. We assessed initial juggling skill acquisition by using criteria based on levels described in an established juggler manual (Finnigan, 1992). In addition, we evaluated all participants' skill development by examining improvement in the spatial consistency of ball tosses during three-ball cascade juggling.

Automatization of juggling was examined in two different ways. The first measure of automaticity, which was based on the average number of consecutive catches between dropped or missed balls, was adapted from Finnigan's (1992) second level of juggling proficiency (i.e., an average of 20 consecutive catches). Automaticity was also measured in the context of a dual-task procedure (cf. Heuer, 1996). In a typical dual-task paradigm, performance of a secondary task, usually an already well-learned, automatic one (e.g., finger tapping or reciting the alphabet quickly) is measured when it is done separately and when it is executed simultaneously with a primary task, and those results are compared. The decline in performance of the secondary task in the simultaneous condition is termed the dual-task cost. Dynamic reductions in the dual-task cost as a new task is learned (vs. more static measures when two already-familiar tasks are performed) are assumed to result from decreases in the demands on processing resources as the primary task is learned and automatized (e.g., Guttentag, 1989), and those reductions are acknowledged to be among the most important and common operational criteria for automatization (e.g., Heuer, 1996). Therefore, a dual-task approach was one of the methods we used to examine the automatization of juggling skills among our learners.

In summary, our interest was in examining the development of the complex skill of juggling. Our specific hypothesis was that we would be able to observe, in the participants' data, progression through the acquisition and automaticity phases of learning the skill of juggling.

**Method**

**Participants**

Ten adults (5 men and 5 women) participated in the study. Six were students at a graduate level of study, and the other 4 were spouses or relatives of the students. The age range of the participants was 23–32 years (M = 27.4 years). None had any previous experience with three-ball juggling. Eight of the participants were right-handed.

**Materials**

Each participant used a similar set of three beanbag balls, each approximately 5 cm in diameter and weighing 50 g. We used a video camcorder to record participants during the probe sessions for later analysis.

**Procedure**

**Training phase.** Training was standardized for all participants; it occurred in one group session of approximately 25 min in duration. Each person was given a written description with accompanying illustrations that outlined the steps of three-ball cascade juggling, and a proficient juggler demonstrated each step. After the training, we videotaped each participant to assess initial skill level (see the Probe Sessions section).

**Practice sessions.** Each participant was required to practice for 15 min a day, five times in a 7-day period, for 5 weeks, for a total of 25 practice sessions. In addition, a 26th practice session was completed after a 1-week break in the juggling rehearsal schedule, which enabled us to determine if juggling performance was maintained after a period of no practice. Participants kept a juggling log of the number of balls caught per juggling trial. A juggling trial was defined as the period from the first ball toss until a cessation of juggling for any reason (e.g., dropped balls, balls crashing in midair, fatigue, and loss of rhythm).

From the practice session logs, several types of data were obtained for each participant: (a) the number of balls caught...
per juggling trial, (b) the average number of catches per juggling trial, and (c) the highest number of consecutive balls caught for each practice session. In addition, the number of the practice session in which each participant reached criteria for various juggling proficiency levels, based on Finnigan’s (1992) juggling manual, was determined. There were two skill levels examined: acquisition and automaticity.

**Acquisition.** True cascade juggling involves at least four consecutive catches (each ball tossed and caught successfully plus the cycle begun again). Acquisition was conservatively defined as an average of at least four catches per trial throughout a 15-min session.

**Automaticity.** A level of 20 catches is one of the criteria recognized by professional juggling instructors as sufficient for a level of achievement certification (e.g., Finnigan, 1992). In the present study, the criterion of 20 catches per trial averaged across all trials in a 15-min practice session was taken to indicate automaticity (see Probe Sessions section for the second measure of automaticity: dual-task cost).

**Probe Sessions**

Immediately following the initial training, then after the 1st, 3rd, and 5th weeks of practice, juggling was videotaped for later coding. Those four probe sessions (Weeks 0, 1, 3, and 5) served as an audit on the self-collected practice session data and provided a second measure of automaticity (based on the dual-task paradigm).

The probe sessions consisted of randomized presentations of two 30-s tests of each of three conditions: juggling only, alphabet only (reciting the alphabet as fast as possible), and dual-task (juggling while reciting the alphabet). Each participant was given a 30-s warm-up period of juggling and was allowed to practice reciting the alphabet as rapidly as possible three times consecutively. There was no practice of simultaneous juggling and alphabet recitation. The numbers of letters recited in the alphabet-only condition and in the dual-task condition were counted, as were the numbers of consecutive catches per juggling trial for the juggling-only and the dual-task conditions. A second person, who was not involved in the study, independently coded 20% of the probe sessions from the videotapes. The average agreement across observations for number of balls of the alphabet recited was .99 (range = .98–1.00), and for number of catches was .98 (range = .89–1.00).

**Spatial Inconsistency**

To determine if skills acquisition was associated with an increased facility in the spatial aspects of juggling in addition to the rhythmic and accuracy components (number of catches), we developed the spatial inconsistency ratio to assess style or appearance. That ratio was defined as the number of throwing errors (erratic balls) divided by the number of throws in a particular test. We determined throwing errors by constructing a rectangular frame for each participant on transparencies. The horizontal dimension of the frame was two times the individual’s width at the shoulders. Vertically, the frame extended a head’s height above the participant’s head and ended at the crotch level. A cross was placed in the middle of the resulting rectangular frame, and that cross was continuously repositioned on the video monitor so that it remained over the sternum as the participant moved. Balls thrown entirely outside the frame were counted as erratic throws; however, balls that were not subsequently caught were excluded from the counts because they ended a trial. The use of the frames therefore allowed for a degree of error in throwing but enabled the identification of extreme errors.

**Reliability**

A second observer independently coded 20% of the probe session juggling tests for spatial inconsistency. The average agreement across observations for number of balls thrown outside the prescribed perimeter was .90 (range = .63–1.00).

**Results**

Because of the limited sample size, the focus in the results is on descriptive statistics, although as will be seen, most of the data showed distinct patterns of outcomes. A summary of results by participant for the practice and probe sessions is presented in Table 1, sorted by the highest mean number of catches per test across the practice sessions. Overall, there were large variations among individuals in their rate of learning and final level of cascade juggling. For example, Participant 2 recorded a mean maximum number of 334 continuous catches per trial across the practice sessions and a single highest trial of 905 catches. Those values contrast with the corresponding scores of 16 and 84, respectively, for Participant 6, and the still lower values for Participant 5.

We first evaluated the hypothesis that the data would show a clear progression through the acquisition and automatization phases of learning to juggle by examining the practice session number at which each participant’s mean number of consecutive catches per trial reached or exceeded 4 and 20, respectively. As is clear from the data in Table 1, there were distinct participant learning types. The first 6 participants listed in the table formed one learning type, termed the proficient group, in which the acquisition criterion was reached in 3 practice sessions or less and the automaticity criterion by 19 sessions. The use of a mean of 20 catches per trial as a measure of automaticity appears to have been a robust criterion, because each of the 6 participants who reached the 20-catch level achieved at least double that level, and all but 1 approached or surpassed an average of 100 consecutive catches per trial. The proficient group also showed the highest performance in the other criteria evaluated and displayed in Table 1.

In contrast, a second learning type, termed the emerging group, which included 3 participants, took close to twice as long to reach the criterion for acquisition (four sessions or more). That group did not reach the automaticity criterion.
TABLE 1. Daily Practice Session and Probe Session Outcome Data, by Learning Type

<table>
<thead>
<tr>
<th>Participant</th>
<th>Gender</th>
<th>Max. av. no. catches</th>
<th>Max. no. catches</th>
<th>Proficient learners</th>
<th>Emerging learners</th>
<th>Late learner</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2</td>
<td>M</td>
<td>334</td>
<td>905</td>
<td>2</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>F</td>
<td>217</td>
<td>540</td>
<td>2</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>M</td>
<td>130</td>
<td>659</td>
<td>1</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
<td>108</td>
<td>389</td>
<td>3</td>
<td>17</td>
<td>8</td>
</tr>
<tr>
<td>1</td>
<td>F</td>
<td>97</td>
<td>310</td>
<td>3</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>41</td>
<td>121</td>
<td>2</td>
<td>19</td>
<td>4</td>
</tr>
<tr>
<td>Group M</td>
<td></td>
<td>154.50</td>
<td>487.33</td>
<td>2.17</td>
<td>10.67</td>
<td>6.17</td>
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<tr>
<td>Group SD</td>
<td></td>
<td>104.95</td>
<td>276.41</td>
<td>0.75</td>
<td>5.96</td>
<td>1.47</td>
</tr>
</tbody>
</table>

Note. Dashes indicate that participant did not reach that level of skill.

of an average of 20 catches per trial in the course of the study. A single participant, who showed a third distinct learning type, is referred to here as the late learner. That participant did not progress beyond the three-ball flash stage of juggling (i.e., she was not consistently able to catch more than three balls in a given trial). Her performance was characterized by the findings that she met the acquisition criterion much later than the other two learning groups did (Practice Session 25) and that she did not reach the automaticity criterion by the end of the study.

The steady growth in performance across practice sessions for the three patterns of performance is shown in Figure 1 for mean catches per trial. There was a corresponding increase in the maximum number of catches per session. The rate of increase in the standard deviations, shown in Figure 1, was generally comparable with the mean number of catches per trial because, as the jugglers became more skilled and better able to catch—for example, 300 balls in sequence—a particular trial might be followed by another in which 20 balls were caught in sequence. In general, the higher the number of balls caught in any session, the greater the probability of a high standard deviation.

The proficient and emerging groups, as well as the late learner, showed other differences in performance on a wide range of variables; the differences between the learning types often approached or exceeded a factor of 2, and the ranges did not overlap. For the practice session data, the learning types differed in the maximum mean catches per trial across all practice sessions (ranges for the proficient group, emerging group, and the late learner were, respectively, 41–334 vs. 13–19 vs. 4) and in the maximum number of consecutive catches made in any trial across all practice sessions (ranges = 121–905 vs. 43–84 vs. 5, respectively). Even in the maximum number of catches in a trial, as early as the first practice session, the ranges were 4–8 versus 2–3 versus 3.

We also examined the probe session data, when juggling was the sole task (i.e., the juggling-only condition). Differences were observed as early as the initial probe session, immediately after an equivalent amount of training was given to each participant and before their first practice session. All participants in the proficient group made an average of at least 20 catches per 30-s test in that session, compared with an average of 9–12 catches for the emerging group and the late learner. Across subsequent probe sessions, participants in the proficient group exhibited a higher mean number of catches per trial (range = 17–105; or 31–105, if Participant 4 is excluded) than did those in the emerging group (range = 8–13) and the late learner (3). Similarly, the proficient group made a higher number of consecutive catches on their best
### Probe sessions data

<table>
<thead>
<tr>
<th>Catches/test in Probe 0</th>
<th>Max. av. no. catches</th>
<th>Max. no. catches any test</th>
<th>Spatial inconsistency ratio, Week 0</th>
<th>Spatial inconsistency ratio, Week 5</th>
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<td>28</td>
<td>31</td>
<td>77</td>
<td>.45</td>
<td>.00</td>
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<td>20</td>
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<td>103</td>
<td>.60</td>
<td>.00</td>
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<td>27</td>
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<td>.77</td>
<td>.00</td>
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<td>23.67</td>
<td>58.00</td>
<td>83.33</td>
<td>.53</td>
<td>.03</td>
</tr>
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<td>3.39</td>
<td>36.96</td>
<td>24.22</td>
<td>.31</td>
<td>.06</td>
</tr>
<tr>
<td>12</td>
<td>11</td>
<td>41</td>
<td>.92</td>
<td>.23</td>
</tr>
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<td>9</td>
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<td>10.00</td>
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<td>1.73</td>
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<td>10.41</td>
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<td>.04</td>
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<tr>
<td>11</td>
<td>3</td>
<td>5</td>
<td>.32</td>
<td>.00</td>
</tr>
</tbody>
</table>

**FIGURE 1.** Mean number of catches per juggling trial during the practice sessions.
trial in the probe sessions, ranging from 41 (77, excluding Participant 4) to 106 catches, versus 26–41 for the emerging group, and 5 for the single late learner.

We also examined automatic performance of juggling by measuring the dual-task response cost in the probe sessions. Response cost was defined as the percentage decrease in the number of letters of the alphabet recited while juggling compared with the number when the alphabet was recited alone (letters recited alone - letters recited while juggling/letters recited alone). A central assumption for evaluating automaticity changes is that although the concurrent task (reciting the alphabet) is automatic, it still shares some processing resources with the juggling task. That finding was demonstrated in Probe Session 0: Compared with reciting the alphabet by itself, reciting the alphabet while juggling resulted in an average of about a 25% decrease in the number of letters recited. If the two tasks were not sharing resources, no such impact would be expected.

The proficient group showed clear evidence of having achieved automaticity, as defined by a reduction in response cost in the dual-task condition, from a mean of 22% to a level close to zero (mean = 1%). The decreases for the emerging group were from 26% in Week 0 to 11%, and, for the single late learner, from 18% in Week 0 to 11% (see Table 2 and Figure 2).

Four of the 6 people in the proficient group showed an actual performance boost in alphabet recitation (i.e., beyond zero interference, to higher performance) on the dual-task as compared with the single-task condition. The magnitude of the inverse response cost ranged from a performance increase of 5% to 15%.

The spatial inconsistency ratio (see Method section) is a measure of the economy of motion that developed, separate from number of catches. That ratio was expected to decrease with increased experience in juggling. Data for Probe Sessions 0 and 5 are shown in the rightmost columns of Table 1. The ratio decreased for all groups, from .53 (or an average of one erratic throw for every two throws) to .03 for the proficient group, from .80 (more than three erratic throws for every four throws) to .19 for the emerging group, and from .32 to .00 for the late learner. Five of the 6 participants in the proficient group achieved an eventual spatial inconsistency ratio of approximately zero (.04), and 4 of the 5 did so by Week 3. Among the other participants, only the late learner achieved a zero ratio, but that was caused by her becoming highly spatially consistent with the flash versus true juggling.

The correlations between the spatial inconsistency ratios per participant and the average number of catches per test were examined for the initial and final probe sessions. The correlations were $r(8) = .21$, $p > .05$, and $r(8) = .47$, $p > .05$, respectively, indicating that the spatial inconsistency data were largely independent of overall achievement.

Finally, although the number of participants was limited, we examined correlations between potential demographic
## Juggling Acquisition and Automatization

<table>
<thead>
<tr>
<th>No. letters (alphabet only)</th>
<th>No. letters when juggling</th>
<th>Response cost (%)</th>
<th>No. letters (alphabet only)</th>
<th>No. letters when juggling</th>
<th>Response cost (%)</th>
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<tr>
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<td>211</td>
<td>12</td>
<td>251</td>
<td>277</td>
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<td>145.0</td>
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<td>197.7</td>
<td>10.7</td>
</tr>
<tr>
<td>47.0</td>
<td>51.8</td>
<td>5.6</td>
<td>28.9</td>
<td>40.5</td>
<td>7.6</td>
</tr>
</tbody>
</table>

| 173                         | 149                       | 14                | 167                         | 148                       | 11                |

### Figure 2

**FIGURE 2.** Mean response cost: Percentage decrement in letters recited (ABCs) in the dual-task condition during the probe sessions.

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variables and outcome and found that neither gender, age, handedness, nor years of postsecondary education was correlated with outcome, although those findings should be treated with caution.

Discussion

Although the number of participants in this study was small (10), outcome measures derived from both practice and probe sessions enabled us to differentiate the participants into three distinct, nonoverlapping learning types: a proficient group, an emerging group, and a single late learner who might well represent a third pattern of juggling skill acquisition. Members of the proficient group acquired and automatized the juggling task quickly and maintained their performance advantage throughout the duration of the study. In contrast, the emerging group took longer to acquire the juggling skill and did not fully automatize the task during the 5 weeks of the study. The late learner took still longer (not until the last week of the study) to acquire the skill and was very far from automatizing. The group differences were quite dramatic in terms of the rate and progression of juggling skill development. Therefore, the hypothesis that the data would show the progression of juggling skill development. Therefore, the

Differences in acquisition of juggling skills were apparent from the initial probe session (Week 0), immediately after the brief training period. Those results were echoed in the first daily practice sessions, with the proficient group catching almost twice as many balls as the other participants. The findings were consistent with the Trussell (1965) juggling study, in that initial facility in accomplishing complex motor skills might predict who the subsequent "stars" will be.

We assessed automaticity by using two different methods. The first criterion—which was chosen on the basis of Finnigan's (1992) juggling manual—of using the session in which the participants achieved an average of 20 catches per trial, was a particularly robust measure of automaticity. Only members of the proficient group reached that mark, and if they attained the 20 catches per trial criterion, they continued on to at least double that score; all but 1 participant in the proficient group made over an average of approximately 100 catches per trial or more by the end of the study. Emerging group members were approaching the average 20-catch mark and, perhaps, would have achieved automaticity had the study been longer in duration. The single late learner was far from automatic performance, having just reached the acquisition criterion at the end of the study.

The second measure of automaticity, the dual-task paradigm, was somewhat more variable at an individual level: participants showed distinctive results, regardless of group membership. Nonetheless, the attainment of automatic performance, as measured by decreasing dual-task cost, discriminated well among the three learning types. Dual-task costs were reduced by the end of the study for all three groups, but only the proficient group demonstrated nearly complete automaticity by a reduction of dual-task cost down to an expected near-zero value.

Moreover, during the concurrent task, 4 of the 6 jugglers in the proficient group demonstrated an inverse response cost—a modest boost in their performance—on the secondary task of repeating the alphabet. That is, performance was better while doing the simultaneous tasks than when performing the secondary task by itself. The inverse response cost, or response boost, is a remarkable finding, because there appears to be no precedent in the dual-task literature for such a boost in performance.

Samuels and Flor (1997) reported an apparent boost in one of their studies, although it appeared in the eventual, post–dual-task performance of the primary task. In the present study, we found a true inverse response cost, that is, a boost in performance on the already-automatized secondary task and while participants performed the dual-task. Despite the differences in the two studies, our interpretation of the response boost is essentially a generalization of the explanation offered by Samuels and Flor. They argued that in dual-task versus single-task conditions, attention is shared in a structured way once the primary task has been learned to a high level of accuracy, and that sharing results in higher performance in the dual-task context. A concurrent task prevents the learner from focusing excessively on the single task (in their case, the primary task) or prevents the learner's attention from "wandering aimlessly," for example, because of boredom (p. 118). Our interpretation is analogous but is generalized to the interaction between both tasks. That is, when one simple task that is highly automatized must be performed alone (e.g., our alphabet task), participants might feel shy or awkward standing in front of a video camera doing such an elementary activity and might focus excessively on the task in order to avoid mistakes. Alternatively, they might be bored with simple repetition of the alphabet, and their attention might wander. Once the primary task of juggling was learned to a high level and thus was not heavily demanding on attentional resources, however, its concurrent performance helped the learners to avoid the pitfalls of excessive or wandering attention, thus resulting in a response boost during our dual-task condition.

The excessive attention view is similar to concepts posited in research into other complex tasks, such as playing tennis or golf. Skilled performers often improve in those tasks by not overthinking or overanalyzing the mechanics but just "doing it" (e.g., Moore & Stevenson, 1991, 1994; Singer, 1988). According to Singer, "it is an overevaluative and aware mind that tends to impair performance potential" (p. 57) in many motor tasks. The provision of a concurrent task might have enabled a release of excessive attentional focus and resulted in higher performance of the already-automatized secondary task in our study. Evidence that the two concurrent tasks must be already well learned for a response boost to occur on the secondary task was provided by the fact that the boost occurred only in the proficient group and...
not among the less accomplished learners. One would need to replicate that interesting inverse response cost finding to verify the particular factors that might lead to an increase in performance when tasks are paired.

It is possible that improvement caused simply by the more efficient coordination of two tasks—for example, the cognitive aspect of keeping track of two activities, or the more physical aspect, such as coordinating breathing with juggling while speaking—might have been a component of the reduction in response cost. Although that component could not be directly evaluated in the present study, the contribution of such coordination was probably not considerable, because the dual task was practiced only at each probe session, that is, for less than 2 min and at four times, each 1–2 weeks apart, for a total of 8 min across 5 weeks. In contrast, juggling was practiced 15 min per session for 5 days per week for 5 consecutive weeks, as well as in the probe sessions; in the latter sessions, juggling was practiced both during the dual-task and on the single-task trials. Therefore, if there was a degree of improvement resulting from coordinating those particular tasks, it was likely overshadowed by the improvement resulting from the much more highly practiced juggling skills that participants brought to the successive probe sessions. However, it would be interesting to examine that question empirically.

The spatial inconsistency ratio quantifies how fluid and proficient a juggler would appear to an onlooker or audience. As early as 1612, Samuel Rid advised that juggling should be "nimblly, cleanly and swiftly done." All participants improved on the spatial consistency dimension. When the ratios were correlated to average number of catches, however, no relation was found, suggesting that spatial consistency and accuracy (number of catches) are two relatively separate entities in juggling, perhaps depending on personal style of learning. As was clear from personal reports as well as from the videotaped sessions, some participants worked toward high numbers of catches while still making a large number of erratic throws, whereas others gave higher priority to consistency of throwing early in learning. However, both types of skills ultimately are needed to achieve high competence in juggling.

One implication of that view is that spatial consistency and number of catches might represent different aspects of skilled performance, one demonstrating control over juggling skills and the other automaticity of the basic components needed to accomplish the task, regardless of form. Throughout much of the literature on automaticity, controlled processes and automatic processes have been hypothesized to represent opposite ends of a single continuum (e.g., Shiffrin & Schneider, 1977). It has also been argued (e.g., Logan, 1988), however, that such a dichotomy is inappropriate and that skilled processes must often be closely controlled. If our spatial consistency data can be seen to represent control over juggling skills, then the lack of a correlation, particularly a negative one, between spatial consistency and accuracy in this study is more in line with Logan's hypothesis, and implies that the relationship between control and automaticity might be orthogonal.

Finally, Ackerman's three-stage theory of skill acquisition provided a general framework with which to study automatization in the present study. The period of learning until the acquisition criterion of an average of four catches would be consistent with Ackerman's (1987, 1988) cognitive stage, in which the demands placed on the learner are in terms of understanding the instructions and planning basic strategies. The single late learner likely remained in the cognitive stage throughout the study. That participant acknowledged that much of her time in the practice sessions was spent trying to develop basic strategies to get past the three-ball flash step (a precursor to true juggling). Ackerman's second, or associative, stage in that context is one in which the fundamental components of juggling have been learned to the point of making very few errors, but participants have not reached automaticity because they are further developing and refining their technique. That stage of skill development is also consistent with Naslund's (1987) concept of mastery, which implies competent performance of a skill, although effortful attention is still necessary. The emerging group appeared to have been in the associative phase or mastery stage; that is, there was competent performance of the skill, although effortful attention was still necessary, and technique was being further developed and refined. Finally, automaticity in this study corresponded to Ackerman's (1988) third, autonomous, stage. The proficient group was in the autonomous stage; their juggling was automatized and required minimal mental effort. Although our groups appeared to parallel Ackerman's stages, additional research to examine movement in greater detail through those phases of learning in complex tasks would be beneficial.

In much of the previous automaticity literature, the focus has been on the learning and performance of fairly simple motor activities, such as tapping or forced-choice key presses. In the present study, we were able to examine the learning and progress toward automatization of a complex motor task. Learning cascade juggling was a highly motivating activity for most of the participants, and such naturalistic types of tasks might prove fruitful for the study of variables such as the development of control versus automaticity in a task or the transfer of learning from one related complex activity to another.

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