AN EXPLORATION OF THE TITRATING-DELAY MATCH-TO-SAMPLE PROCEDURE WITH PIGEONS

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Thesis Prepared for the Degree of

MASTER OF SCIENCE

UNIVERSITY OF NORTH TEXAS

December 2011

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Friedel, Jonathan E. An Exploration of the Titrating-Delay Match-to-Sample Procedure with Pigeons. Master of Science (Behavior Analysis), December 2011, 37 pp., 6 Figures, references.

The delayed matching-to-sample procedure involves the insertion of a delay between the offset of a sample stimulus and the onset of an array of comparison stimuli; one of which is designated as the "correct' match for the sample on each trial. The procedure has served as the base preparation in which the effects of environmental variables on short-term remembering and is, in many ways, responsible for a refined understanding of the phenomenon. Despite its utility, however, there are a few problems with the DMTS procedure – first, the procedure doesn't adjust for individual differences and second, the conventional dependent measure, percent of correct trials, is not as sensitive as one might like. The titrating-delay matching to sample (TDMTS) procedure is a variant of the DMTS procedure in which the delays between sample and comparison are adjusted as a function of the subject's performance. Stable measures of adjusted delay are not only sensitive measures of the performance of interest but they are also automatically tuned to differences across individuals. The study reported here continues our efforts to understand the dynamics of the TDMTS procedure so that it can be used to ask important questions related to short-term remembering.

ACKNOWLEDGEMENTS

I would like to thank Ryan Brackney, Jay Hinnenkamp, Caleb D. Hudgins, Bryan Lovelace, and Madonna Ludlum for help with collection of these data.

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INTRODUCTION

Issues relating to memory and remembering have been of sustained interest to psychologists since the beginning of professional psychology resulting in over 1000 models and theories about the structures and mechanisms underlying the phenomenon (Watkins, 1990). Behavior analysts have also been interested in the topic but have approached it from a more utilitarian angle or perspective. For behavioral psychologists, the word “remembering” refers to behavior that is controlled by stimuli that are no longer present in the current environment (Blough, 1959; Branch, 1977; Jans & Catania, 1980). In a related way, “forgetting” refers to the loss of that stimulus control over time (White, 1985). From a behavior analytic perspective, then, the experimental issues of interest in remembering and forgetting involve identifying the environmental conditions under which stimulus control is maintained in the absence of the stimulus and the variables that attenuate or exacerbate the decay of stimulus control over time.

In behavioral laboratories, remembering has primarily been studied using delayed matching-to-sample (DMTS) procedures (Blough, 1959; White, 1985; White & Wixted, 1999; but see, Wright, 2007, for a discussion of alternative methodologies). A typical DMTS trial begins with the presentation of a stimulus – called a sample stimulus. A response to the sample stimulus, often called an observing response, is required to move the trial forward. The observing response removes the sample stimulus from the environment and after some period of time, called the retention interval (RI), presents an array of stimuli called comparison stimuli. A response to the experimenter-designated correct comparison stimulus is followed by the presentation of food or some other known reinforcer and a response to any other stimulus in the comparison array leads either to no programmed consequence or the presentation of known punishers. The primary dependent variable in this preparation is percent of correct trials as measured across a variety of RI values.

The DMTS procedure has led to important advances in our understanding of the environmental determinants of remembering and forgetting. The procedure, for example, has facilitated cross-species comparisons of memorial processes (White, in press) and, recently, has been used to study memorial processes in aging adult humans (Edhouse & White, 2003). Interpretation of the results of the procedure has also benefitted from quantitative analyses of obtained performances (White, 2001). For example, it has now been widely established that the loss of stimulus control over time is seen in a variety of species and is best described by an exponential decay function (White, 1985; White, in press). Furthermore, remembering is now understood as being a combined function of at least three dissociable variables: how discriminable the stimuli are from each other (as reported by the subject) when a report is required with no delay (hereafter, the initial discriminability); the amount of time that elapses between the learning and the report (hereafter, the retention interval); and the rate at which the stimulus control decays over time (White, 2001; White, in press). Researchers have identified, for example, that manipulating variables related to the sample stimuli (such as exposure time or similarity to other stimuli) affects the discriminability but not the rate at which stimulus control decays (Foster, Temple, Mackenzie, DeMello, & Poling, 1995; White & Wixted, 1999). Similarly, variables operating during the RI (such as the presence of distractors) affect the rate of forgetting but do not change initial discriminability (Grant, 1988; White, 1985). Taken together, the findings described above represent a significant advance in our understanding of the influence of environmental variables on remembering and forgetting.

Although the DMTS procedure has been useful in advancing our understanding of the development and decay of stimulus control, a few features of the procedural and conventional data-analysis methods hinder a full and nuanced understanding of environmental influences. One limitation of DMTS preparation is a "ceiling effect" introduced by the fact that the percent-of-correct-trials measure is capped at 100%. This arbitrary limit does not allow researchers to discern the full effect of environmental variables when performance is already highly accurate (see Alsop, 2004 and Brown & White, 2005 for an extended discussion of ceiling effects). Improvements in highly accurate performance that may be detected by other measures such as latency are not noticeable when percent-of-correct trials serves as the main dependent measure. This ceiling effect, then, limits the scope of questions we ask with the DMTS procedure.

A second limitation is that, as typically arranged, DMTS procedures do not take into account the possibility that individual subjects may differ along a variety of dimensions that may impact the performance of interest. But DMTS procedures ask all subjects in a given study the same question – i.e., "Does our IV manipulation allow you to remember more accurately at the 10-second delay than you could before? Yes or No?" The results, of course, show individual differences but the procedure and the measurement system do not allow for a mechanism by which the differences can lead to alterations in the procedure.

A variant of the DMTS procedure that minimizes the limitations identified above by asking different questions is the titrating-delay match-to-sample (TDMTS) procedure (Cumming

& Berryman, 1965). The TDMTS procedure is similar to the DMTS procedure with the difference that the RI value is adjusted, on a trial-by-trial or block-by-block basis, by the subject's performance accuracy on some number of previous trials. For example, Cumming and Berryman (1965) arranged for the RI to increase by 1 s if the pigeons chose the matching comparison stimulus on two consecutive trials and to decrease by 1 s following one incorrect choice. This adjusting procedure, then, gives rise to a dynamic and sensitive measure – namely, the value of the adjusting RI (Kangas, Vaidya, & Branch, 2010). This procedure effectively addresses the two concerns raised above: 1) the main dependent measure is not subject to the same ceiling effects as percent-of-correct-trials because the adjusting RI value can adjust virtually without limit[1]; 2) the main dependent measure is sensitive to individual differences because each bird's performance determines the value of the adjusting RI it experiences. In more colloquial terms, every subject is asked a question that is adjusted to the subject's demonstrated capabilities.

Although the TDMTS procedure has been available for well over 40 years, there has been little systematic work undertaken to map out the role of a variety of variables on the phenomena of interest in the procedure. For example, the rules by which the delay adjusts up or down are logically related to the dependent measure but there has been no systematic study of such parameters on the resulting performances. Some labs arrange for the delay to adjust up after one correct response and to adjust down after one incorrect response or (Buccafusco, Terry, Jr., Goren, & Blaugrun, 2003; Buccafusco, Terry, Jr., & Murdoch, 2002); others have used different adjustment parameters such as 2 correct: 1 incorrect (Ferraro, Francis, & Perkins,

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[1] Of course, number of trials programmed and time limits on sessions impose different kinds of ceiling effects, but these are logistical issues and not inherently due to the properties of the dependent measure

1971; Kangas et al., 2010; Scheckel, 1965), and 3 correct: 2 incorrect (Jarrard & Moise, Jr., 1970). In all of the above studies, except Kangas et al., 2010) the adjusting RI was used as an index of some other independent variable such as the effects of a monoamine-oxidase cholinesterase inhibitor (Buccafusco et al., 2003), an index of the effects of picrotoxin to help determine the binding sites of pentobarbital, diazepam, and phencyclidine (Wenger et al., 1996), or the effects of restraint on TDMTS performance. In all of these studies, the TDMTS procedure was not being investigated for its own sake and the procedure was being utilized without necessarily understanding the dynamic interactions of the various components of TDMTS.

Over the last few years, our lab has attempted to explore the effects of various procedural variables on the main dependent measure of the TDMTS procedure – the adjusted RI (Kangas, 2005; Levine, 2009, Lovelace, 2008). The goal of these studies has been to explore the effects of various classes of variables on pigeons' and humans' performance on TDMTS procedures, particularly as measured by the adjusting RI.

Kangas et al. (2010), for example, described three experiments investigating the effects of various procedural variables on the adjusted RI. Experiment 1, investigated the effects of increasing sample stimulus observing-response requirements across conditions and found that doing so increased the value of the adjusted RI and decreased the rate at which stimulus control decayed over time. These data were partially consistent with a common finding in the DMTS literature – that increasing time spent observing the sample stimulus improves accuracy of comparison selections at various RI values (Grant, 1988).

In Experiment 2, Kangas et al. (2010) worked with different subjects and manipulated the initial RI value at the start of the session to ascertain whether the obtained RI values were reproducible under otherwise similar environmental conditions. Subjects began sessions with the RI either equal to 0 s or twice the value of the average RI obtained by the same subject during a replication of Experiment 1. All subjects' performances titrated the adjusting RI in the direction of the average RI observed during Exp. 1. That is, subjects who began with very high RI values were more likely to make errors resulting in downward adjustment of the RI and subjects who began at 0-second were more likely to match accurately resulting in upward adjustment of the RI. These data suggest that the dependent measure in TDMTS procedure is robust and replicable and not exclusively determined by the initial value of the RI.

In Experiment 3, Kangas et al. investigated the effects of the titration step-size on the value of the adjusted RI. All subjects were exposed to a reversal design in which the RI adjusted by 1 s increments in the first condition, 2 s increments in the second condition, and returned to 1 s increment in the third condition. The researchers found that increasing the titration step size increased the variability in the adjusting RI measure (during the second condition) but did not affect the mean value of the adjusting RI. As in Experiment 2, these data are interesting because they show that the obtained RI value is not exclusively determined by the size of the titration parameter over the range of 1-2 s. The three experiments reported by Kangas et al. (2010) represent one of the few attempts to try and understand the role of procedural variables on performance in TDMTS procedures.

The aim of this report is to extend Kangas et al. (2010) and expand our understanding of TDMTS as a procedure. For the purposes of the current discussion, the variety of environmental variables shown to affect remembering in the TDMTS procedure can be categorized into three broad classes – variables manipulated within the bounds of a trial such as observing response requirements, variables manipulated between trials such as the inter-trial interval (ITI) or the criteria for adjusting the RI, and variables manipulated across sessions such as the initial value of the RI across sessions. Accordingly, the following report presents three comparisons comprising one study: a comparison of within-trial variables, a comparison of across-trial variables, and a comparison of across-session variables. The effects of these independent variables was measured via the dependent measure of stable adjusted RI values and forgetting functions

In a titrating-delay match-to-sample (TDMTS) procedure, the criteria for titrating the retention interval (RI) result in a particular global accuracy when performance is stable (Wenger & Wright, 1990) and performance accuracy exceeding that requirement will suffice to increase the adjusting RI. For example, if one correct response increases the RI and one incorrect response decreases it, the global accuracy of stable performance (in which the adjusting RI value oscillates between two values) would be around 50% correct. Under these conditions, performance accuracy exceeding 50% correct would be sufficient to adjust the RI upward despite the fact that in a two choice procedure an accuracy of 50% is chance performance and an indicator of a lack of stimulus control. As Sidman (1987) has pointed out, it is even possible to maintain 75% accuracy in a two-choice match-to-sample (MTS) procedure even though only one of the two conditional relations has actually been acquired. Imagine, for example, a hue matching task with two colors, red and green. The subject may match with perfect accuracy on trials with red samples (100% correct) and perform only at chance levels of accuracy on trials with green samples (50% correct). Such a state of affairs would still produce a global accuracy of 75% correct. As Sidman (1987) suggests, the relatively high value of the dependent measure (75% correct) can overestimate the obtained degree of stimulus control. These considerations can be important as we attempt to ask questions about the decay of stimulus control as a function of time or other variables.

Kangas et al. (2010, Exp. 1) examined the effects of observing-response requirements on the value of the adjusted RI and found that increasing the observing response requirements also increased the adjusted RI value. In their study, two consecutive correct responses increased the RI by 1 second and one incorrect response decreased the RI by the same value. When the performance is stable over extended exposure, these criteria would be expected to yield a global accuracy of 66.67% correct. Again, as described by Sidman and others, this accuracy level may be achieved even when the nominal stimuli fail to completely control the response in question (as in the case of position biases or stimulus preferences). Is it possible that the effects of increasing observing-response requirements seen in Kangas et al. (2010, Exp1) were related to the fact that minimal control was required by the nominal stimuli?

The first comparison in this report was a systematic replication of Kangas et al. (2010, Exp. 1). Subjects were exposed to three conditions with 1, 8 or 16 observing-responses required to move the trial forward. Unlike the Kangas et al. study, however, the criteria for adjusting the RI were set at 6:1 – that is, six consecutive correct responses increased the RI by 1 second and one incorrect response decreased the RI by 1-second. When performance is stable, these criteria would be expected to yield a global accuracy of 85.7% correct and increase our confidence that each subject's performances were under control of the nominal stimuli and not based on a hue or position bias.

Method

Subjects. Four experimentally naïve White Carneau pigeons (Columba livia) obtained from Double-T farms served as subjects (739, 710, 648, & 691). The subjects were housed in individual cages in a temperature- and humidity-controlled vivarium with a maintained 12 hour light/dark cycle. The subjects had continuous access to water and health-grit while in their home cage and were maintained at 80% of their ad libitum weight via postsession feedings as necessary. Sessions were conducted six days a week at approximately the same time every day.

Apparatus. Sessions were conducted in a 30 cm x 30 cm x 50 cm light- and sound-attenuating chamber equipped with an exhaust fan to provide ventilation and masking noise. The intelligence panel comprised one wall of a wooden chamber and was made out of a sheet of aluminum measuring 30 cm x 30 cm. The panel consisted of a houselight, three-horizontally arrayed response keys and an opening for a food hopper. The houselight was mounted 3 cm below the ceiling in the horizontal center of the panel. Three response keys, measuring 2.5 cm in diameter, were mounted 25cm above the floor and 8 cm away from each other. Access to the solenoid-operated food hopper was provided through a 6 cm by 6 cm opening in the horizontal center of the panel and 10 cm above the floor of the chamber. They keys could be transilluminated with colors and shapes using inline projectors (IEEE, #ENV-130M). Scheduling of experimental events and data collection were controlled via Med-PC software (Ver 4.0, Med Associates, St. Albans, VT) running on an IBM compatible computer with a Pentium III processor.

Procedure. Pretraining. Each pigeon was first placed in the chamber for one hour with the house light turned on and no other programmed stimuli to allow the animal to adapt to its experimental environment. The pigeons were then trained to eat food from the hopper when it was raised. Access to the hopper was then made contingent on successive approximations to pecks on the center and side keys when illuminated. Pretraining was considered complete when the birds reliably pecked any of the three keys when it was transilluminated with white light.

Training simultaneous matching-to-sample. Subjects were next taught to match red and yellow hues in a simultaneous matching-to-sample procedure. Trials began with the onset of the houselight and the illumination of the center key with either red or yellow hue (hereafter, the sample stimulus). A single peck on the center key illuminated the side keys with red and yellow hues which appeared on either key with equal probability (hereafter, comparison stimuli). A single peck on the side key that was illuminated with the hue matching the sample stimulus resulted in the offset of the houselight, offset of all key lights, and the simultaneous onset of the hopper light and presentation of the food hopper for two seconds. A response to the nonmatching comparison stimulus turned off the houselight and all key lights and initiated a brief time-out which was equal to the duration of hopper access programmed on correct trials. Either consequence was followed by a 10-s intertrial interval during which all lights in the chamber were off. If at any point a subject was demonstrating persistent bias, either to a specific hue or position, a correction procedure was arranged for an entire session in which a trial with an incorrect response was presented again until the subject made a correct response. The training was considered complete and conditions were changed individually when a subject's performance was greater than 90% accurate for 9 out of ten consecutive sessions, no session accuracy was below 70%, and none of the sessions within the range contained correction procedures.

Training delayed matching-to-sample. Subjects who met the acquisition criteria described above were then exposed to a delayed matching-to-sample (DMTS) procedure with a zero second delay programmed between the offset of the sample stimulus and the onset of the comparison array. All other details were identical to the training conditions described immediately above. The correction procedure described above was implemented anytime the subjects developed a position or stimulus preference in the 0-s DMTS condition. Training continued until the subjects met the same stability criteria for the previous condition.

Titrating-delay match-to-sample. Subjects were exposed to the first experimental condition after all training was complete. The TDMTS procedure was identical to the DMTS training described above with a few differences. First, the RI value was set to adjust as a function of the subject's performance – six consecutive correct matches increased the delay by 1-second and one incorrect match decreased the delay by 1-second (unless the RI was already at its minimal value). Second, instead of resetting the RI to zero at the beginning of every session, the initial value of the RI (on the first trial of a session) was carried over from the last trial of the previous session. All other details were identical to the DMTS training conditions specified above. All subjects were exposed for a minimum of 10 days to each condition. Stable performances were required before a change to a new experimental condition was made. Stability criteria were required that 9 of the subject's last ten days of performance be within 25% of the mean of those ten days (cf., Kangas et al., 2010) with no visible trend and the first and last data points in the 10-day window could not be the highest or lowest points.

The initial observing response requirement for those subjects was an FR1, prior to the offset of the sample stimulus and the onset of the RI. Once the subjects' performances were stable, they were transitioned to an observing response requirement of FR8, all other trial features were held constant. Finally, once subjects' performances were stable, they were transitioned to an observing response requirement of FR16. One subject, 648, displayed highly variable, but otherwise stable performance for an extended period with the FR8 condition and was not transitioned to the FR16 condition. All other conditions for this subject (comparison 2 and comparison 3) had an FR8 observing response requirement.

Results

All four birds acquired the simultaneous MTS performance in 15 sessions, on average. The minimum number of sessions required was 10 (Subject 710) and the maximum was 17 (Subject 739). All four subjects acquired the 0” DMTS performance in 52 sessions, on average. The minimum number of sessions required was 22 (Subject 710) and the maximum was 132 (Subject 648). There was nothing else noteworthy about the birds’ acquisition of the simultaneous MTS performance or the 0” DMTS performance and nothing more will be said about this part of their training.

Figure 1 presents data from all of the observing-response conditions for each of four subjects. The bars present the mean of the adjusted RIs from all trials in the last 10 sessions in each condition. The ordinate has been scaled logarithmically to facilitate comparison of the adjusted RI in all conditions.

Figure 1 shows that the value of the adjusting RI increased as a direct function of the observing response requirement for all birds. For Subject 648, the adjusted RI was .18 s for the FR1 condition and increased to .43 s in the FR8 condition. For Subject 691, the adjusted RI was .17 s in the FR1 condition, increased to .38 s in the FR8 condition and to 5.21 s in the FR16 condition. For Subject 739, the adjusted RI was .28 s in the FR1 condition, increased to 1.43 s in the FR8 condition and to 2.15 s in the FR16 condition. For Subject 710, the adjusted RI was .19 s, .24 s, and .36 s, in the FR1, FR8 and FR16 conditions, respectively.

Once data were collected for each experimental condition, forgetting functions were plotted for each subject per condition. In this study, because the number of exposures to a specific delay value are determined by the subject, logit p (logit p = $\log_{10}(p/(1-p))$ where p is the proportion correct) was used. Standard forgetting functions (utilizing log d measures, White, 1985) are subject to maximum obtainable values, where the total number of exposures to a RI set an upper limit on maximum obtainable log d value for that RI. The ratio of proportion correct to proportion incorrect, logit p, is a better measure in these comparisons because it is not subject to the maximum obtainable value and is scalable when the number of exposures to specific RIs cannot be held constant. Negative exponential growth curves were fitted to the obtained logit p values to generate forgetting functions (White, 1985) That is,

$$\mathrm{logit}\ \mathrm{p} = \mathrm{logit}\ \mathrm{p}_0 \ \times \ \mathrm{e}^{-\mathrm{bt}}$$

where p_0 is the initial discriminability, b is the rate of stimulus control decay, and t is the RI.

Figure 2 presents forgetting functions for each observing-response requirement for each subject. The data show that increases in observing-response requirements were correlated with decreases in the rate of forgetting for all subjects across all conditions. For all subjects, there is a direct, inverse relationship between the observing response requirement and rate of forgetting (b), as the observing response requirement increase the rate of forgetting decreases. Subjects 648 and 691 have the largest decreases in the rate of forgetting when transitioned from FR1 to FR8. Their rates of forgetting are, respectively, 56.77 for FR1 and .63 for FR8 and 65.60 for FR1 and 1.27 for FR8. Subject 691 also had a decrease in b when transitioned to the FR16 condition, decreasing to .05. Subject 710 had decreases in the rate of forgetting as the observing response requirement increases that were seemingly regular decreases from 3.49, to 2.37, to 1.41. 739 had decreases in the rate of forgetting from 2.47, to .47, and finally .13 in the FR16 condition.

The effects of observing-response requirements on the y-intercept (interpreted as initial discriminability) are inconsistent. For Subject 739's, log p_0 values were the same for the FR1 and FR8 conditions and decreased during the FR16 condition. For Subjects 710 and 648, the effect was just the opposite – increases in observing response requirements were correlated with increases in log d_0 values suggesting an increase in the initial discriminability of the stimuli. For Subject 691, the increase in observing response requirements produced both an increase (.82 in the FR1 condition to 1.50 in the FR8 condition) and a decrease (1.12 in the FR16 condition) in initial discriminability.

Discussion

The results show that, for all subjects, the adjusting RI value increased as observing-response requirement was increased (though the size of the increase in the RI varied across birds). This finding replicates a standard finding in the DMTS literature that an increase in time spent observing the sample stimulus leads to greater matching accuracy at longer delays. In the traditional DMTS preparation, however, the increased accuracy is the result of increases in initial discriminability and not a decrease in the forgetting rate (White & Wixted, 1999; Grant, 1988) The data from Figure 2, however, show that the improvements in accuracy at longer delays were largely the result of observing-response-requirement related decreases in the rate at which stimulus control decayed over time. This finding is contrary to similar results utilizing DMTS in which the effect is seen primarily in the initial discriminability. The discrepancy could be due to differences in the two procedures. For example, in a standard DMTS procedure, the RI values are identical regardless of the observing-response requirement in effect. In the TDMTS procedure, the subject experiences multiple RI values. Could that difference account for the difference in the results between DMTS and TDMTS procedures? A direct comparison between manipulations of the observing response requirement in TDTMS and DMTS could help tease this apart.

The stable adjusted RI values reached in this comparison are lower than those of experiment one in Kangas et al. (2010). While a within subject comparison would be the most direct way to answer the question, the titration parameters likely played a role. The value of the RI in the current study was increased by one second following six consecutive correct matches as opposed to two consecutive correct matches in Kangas et al. (2010). The criteria for increasing the adjusting RI were far more stringent in the current experiment than in Kangas et al. (2010).

COMPARISON 2

One possibility, other than a more stringent criteria for increasing the retention interval (RI), as to why the stable adjusted RIs were higher for experiment one of Kangas et al. (2010) than in Comparison 1 is that by the direct ratio the 6:1 is much more sensitive to errors. Because of the complex state of titrating-delay match-to-sample (TDMTS) research, little is known about the affects a less stringent parameter for decreasing the adjusting RI. In this experiment a direct ratio of 6:2 was arranged as the titration parameters for a TDMTS procedure, where six consecutive correct responses were required to increase the adjusting RI and two consecutive incorrect trials were required to decrease the adjusting RI. In this way a subject must now be "reliably" inaccurate to decrease the RI.

Method

Subjects. The same four subjects from Comparison 1 served as subjects for this comparison.

Apparatus. The apparatus was the same as described above in Comparison 1.

Procedure. All details in this comparison were identical to the last condition in Comparison 1, with two exceptions. First, the rule by which the RI adjusted downward was changed from 1 consecutive incorrect response to 2 consecutive incorrect responses. Second, two of the birds (739 and 691) were transitioned to a subsequent condition despite the fact that their performance was not stable by our definition (detailed below). It is important to note that in the previous comparison subject 648 was only exposed to an FR8 observing response requirement. That observing response requirement was still in effect for this subject in this condition while all other subjects were exposed to an FR16 observing response requirement.

Results

Figure 3 presents the data from the last condition of Comparison 1 and from the current condition in which two consecutive incorrect responses were required to adjust the RI downward. In both cases, the bars present the mean of the adjusted RIs of the last 10 session in each condition (691 only had 6 sessions in total for the entire condition). The error bars represent one standard deviation around the mean value. It is important to note that while this Figure is similar in kind to Figure 1. For Subject 710, the mean RI value increased .37s to 1.97s. For 648, the mean RI value increased from .43s to 2.27s. For 739, the mean RI value increased from 2.15s to 6.75s. Finally, for 691 the mean RI value increased from 5.2s to 9.05.

Subjects 739 and 691 were moved into the next condition despite the fact that their performances were not stable by our definition. For 739, whose mean RI values were regularly in the 5 – 7 second range prior to discontinuation of the condition, with occasional adjusted RI values as high as 11 s, latencies to respond to the sample stimulus began to increase until the bird was waiting approximately 20 - 60s on average to start a trial. Subject 739 was often unable to finish sessions in the two-hour limit imposed on session durations. For 691, whose mean RI values were regularly in the 10-13 second range prior to discontinuation of the condition, latencies to initiate the observing response similarly increased. We predicted that the next planned comparison would address the latency issues and moved the birds to the next planned condition.

Figure 4 presents the forgetting functions derived from the obtained logit p values each condition in Comparison 2 for each subject. There is no general trend in the initial discriminability across subjects. Two subjects, 710 and 648, have decreases in initial discriminability, from 1.75 to .65 and from 1.14 to .72, respectively. Subjects 739 and 691 had increases in initial discriminability. Subject 739's initial discriminability increased from 1.12 to 1.24 and subject 691 had an increase in initial discriminability from 1.12 to 1.26. While the differences in the initial discriminability across subjects are mixed, there is a consistent decrease in the rate of forgetting for all subjects. Subject 739 and 691 had small decreases in the rate of forgetting, from .13 to .10 and from .05 to .03, respectively. Subject 710 had the largest single decrease in the rate of forgetting, from 1.41 to .40. The scale of the decrease in the rate of forgetting for subject 648 lies between the other subjects, decreasing from 1.14 to .72.

Discussion

The mean RI values for all subjects increased when the number of errors required to adjust the RI downward was increased from 1 error to 2 consecutive errors. The increases in the adjusting RI in this comparison brings the subjects closer to the adjusted RIs obtained in experiment one of Kangas et al. (2010), though the absolute values reported here are still much lower. Both subjects 739 and 691 show little difference in their respective forgetting functions when transitioned from the 6:1 to 6:2 condition. For both of these subjects, the changes in the rate of forgetting were so small that the forgetting functions between conditions are almost identical in slope. The results for Subjects 710 and 648 are more difficult to interpret. Subject 710 has large changes in initial discriminability and the rate of forgetting between conditions. Subject 648 has more moderate changes in initial discriminability and the rate of forgetting.

COMPARISON 3

One potential issue limiting the generality of the findings in Comparisons 1 and 2 as well as the findings from Kangas et al. (2010, Exp. 1 & 3) is that the aforementioned studies used the last value of the adjusting retention interval (RI) of one session as the beginning value of the next session. This feature of the current studies is uncommon in that the typical procedure involves starting each session with RI set at 0 s. It is not known if this difference, the initial conditions of a titrating-delay match-to-sample (TDMTS) session, is an important variable in regards to the stable adjusted RI. Experiment 2 of Kangas et al. (2010) partially addressed this issue. Subjects in that experiment were exposed to TDMTS sessions where the initial adjusting RI for a session was either zero seconds or a value that was twice some previously determined stable adjusted RI value. In this way, Kangas et al. (2010) were able to compare the effect of starting value on the final value of the RI.

Method

Subjects. The same four subjects from Comparisons 1 and 2 served as subjects for this comparison.

Apparatus. The apparatus was the same as described above in Comparison 1.

Procedure. All details in this comparison were identical to those in Comparison 2, with two exceptions. Firstly, the initial RI for a session was always zero seconds as opposed to the terminal adjusting RI for one session serving as the initial adjusting RI for the next session. Secondly, the special circumstances that led to us having to arrange a new condition prior to determining stability in the subjects performance was no longer necessary. All subjects continued in this condition until they met stability criteria.

Results

Figure 5 presents the data from the last condition in Comparison 2 as well as from the current condition in which the adjusting RI was zero seconds at the beginning of every session. For both conditions, the bars represent the mean of the adjusted RIs of the last 10 sessions in each condition. The error bars represent one standard deviation from the mean value. Similar to Fig. 3, the ordinate is a linear scale. The stable adjusted RI values for this condition are mixed. Subjects 739 and 691 show sizable decreases in the stable adjusted RI values, from 6.74 s to 3.81 s and 9.05 s to 4.17 s, respectively. Subject 710 shows a small decrease in the stable adjusted RI, from 1.97 s to 1.65 s. Subject 648 is the only subject who shows an increase in the stable adjusted RI when transitioned to an arranged TDMTS with a resetting delay, increasing from 2.27 s to 2.65 s.

Figure 6 presents the logit p forgetting functions for Comparison 3 for each subject. For all subjects the TDMTS with the resetting delay leads to higher initial discriminability, with differences in the scale of the change. Subjects 739 and 691 have minor increases in the initial discriminability with increases of .10 and .05, respectively. Subjects 710 and 648 have more substantial increases in initial discriminability, changes of .55 and .81 respectively. Generally, when transitioned to the resetting condition subjects demonstrated decreases in the rate of forgetting; only subject 648 had increases in the rate of forgetting. Subject 648's rate of forgetting decreased from .26 to .29. All other subjects demonstrate decreases in the rate of forgetting when transitioned to the second condition. Subject 739 decreased from .10 to .07, subject 710 decreased from .40 to .34. Subject 691 rate of forgetting decreased minimally from .03 to .02.

Discussion

It appears from results of this comparison that the effect of resetting the RI to zero at the beginning of every session depresses the adjusted RI. However, the obtained forgetting functions for the conditions in Comparison 3 are not in line with this finding. If the subjects were "remembering less" that result should be mirrored in the forgetting functions. The obtained forgetting functions of 739 and 691 show little difference across conditions, and are once again almost respective sets of parallel lines like in Comparison 2. Subjects 710 and 648 show small differences in the rate of forgetting and have higher initial discriminability in the resetting condition. It is likely that the differences in the stable adjusted RI between these conditions are parameter-related and not remembering-related, or that there is minimal difference to the decay of stimulus control over time the changes are the result of differences in how we test for that decay of stimulus control. The large decreases in the stable adjusted RI are caused by starting sessions with a 0 s RI as opposed to an adjusted RI from the previous session.

It may be the case that with a resetting TDMTS average adjusting RI is not an appropriate measure. In a TDMTS where the RI is carried over and the stable adjusted RI has been reached, the average RI for a session should be at or near that stable adjusted RI. In a resetting condition, however, the average RI represents the transition from a 0 s RI towards that stable adjusted RI. A resetting TDMTS procedure may be better served by dependent measures of the maximum RI obtained for the session, number of trials to the maximum RI, and the frequency distribution of obtained RIs.

GENERAL DISCUSSION

In general, the results of this experiment are similar in kind to the results obtained in Kangas et al. (2010); that is, the titrating-delay match-to-sample (TDMTS) is a robust procedure and the adjusting retention interval (RI) is a reliable and replicable dependent measure. The findings of Comparison 1, that increases in observing response requirement lead to higher stable adjusted RI values, though different in absolute value, are the same as experiment one and remembering research utilizing standard delayed match-to-sample (DMTS). Comparison 2 demonstrated that increasing the consecutive number of incorrect responses required to decrease the titrating RI, thus making the task less sensitive to errors, leads to higher stable adjusted RI values is a novel contribution to our understanding of TDMTS that is in line with our previous understanding of the procedure. Our last comparison indicates that the stable adjusted RI is a reliable measure, and like Experiment two of Kangas et al, subjects will titrate the RI towards some stable adjusted delay value. None of the comparisons reported here contradict the findings of Kangas et al. (2010) and the combination of the findings reported here and in that study point towards a reliable procedure to studying remembering.

One of the more intriguing findings here is that only variables that were changed within trials seemed to have a major effect on remembering. The variables manipulated in this experiment include within trial manipulations, across trial manipulations, and across session manipulations. The manipulation of within trial variables in this experiment are the observing response requirements reported in Comparison 1. The manipulation of across session variables included the parameters by which the adjusting RI was titrated in Comparisons 1 and 2. Finally, the manipulation of the initial conditions of the TDMTS session were changes in variables across sessions. Figure 2 shows the substantial differences in forgetting functions that occur when the observing response requirement is manipulated, a within trial manipulation. There are small and, for subjects 710 and 648, disordered differences seen in in forgetting functions in the three conditions that comprise Figures 4 and 6. That there is a similarity in the forgetting functions of Figures 4 and 6 leads us to hypothesize that titration parameters do not lead to changes in remembering, and a thorough investigation of that possibility is necessary.

The TDMTS procedure still accommodates individual differences better than the standard DMTS procedure. In this case, when all of the subjects have reached their respective stable adjusted delay value they all equally as accurate across trials (Wenger et al., 1990). If we introduce or change some variable that will change a subject's accuracy then we should see a shift in the adjusting RI, but once all of the subjects restabilize they will all be at that same level of accuracy. The TDMTS procedure provides accommodation of individual differences while holding accuracy across subjects stable and this may be a beneficial state for many experimental questions.

An important issue to consider when interpreting adjusting RIs is that reported value is meaningless without the experimental variables and experimental context in which the value was obtained. Comparisons 2 and 3 demonstrate noticeable differences in adjusting RIs across the 6:1 Carryover, 6:2 Carryover, and 6:2 Resetting conditions but do not have similar changes in the forgetting functions for those conditions. Similarly, adjusting RIs in experiment one in this report are lower than adjusting RIs for identical observing response requirements in Experiment 1 of Kangas et al., (2010). The similar forgetting functions in Comparisons 2 and 3 indicate that the differences in adjusting RIs do not appear to be remembering related. Without specifying exactly what the criteria of titration are, it is extremely difficult to compare adjusting RIs across conditions, subjects, and experiments. Similarly, when utilizing TDMTS one of the major findings of this experiment is that it is important that the parameters by which you titrate the RI must be consistent across conditions. The measures of stable adjusted delay, maximum delay experienced per session, or trials to maximum delay will change based on titration parameters, but these changes may not be processual changes of remembering. By keeping the titration parameters constant across conditions it is unlikely that dependent measure changes will be the result of those parameter changes.

When subjects were transitioned in Comparison 2 from a titration schedule where they will be 85.7% accurate when the adjusting RI has stabilized to a titration schedule with a 75% accuracy, stable adjusted RIs increase. This leads to two simple experimental questions which were not addressed in this report. 1) Does the accuracy level engendered by the titration schedule lead to a certain stable adjusted RI or do the specific criteria for adjusting the RI lead to a stable adjusted delay value? In Comparison 2 of this experiment we arranged a 6:2 titration schedule, arranging a 75% accuracy level at the adjusting RI. 2) Is the ratio between correct and incorrect responses important or are the specific values important? For example, is a 6:2 ratio schedule the same or different than a 3:1 ratio titration schedule? They both will result in the same accuracy level, but the point at which you can maintain six correct responses before two errors occur, on average, may be different than the point at which you can maintain three responses before an error occurs. It will be important to establish, precisely, the answer to these two questions.

An issue of key importance to understanding the behavior and environment interactions when using TDMTS is the titration parameters. There is likely an inverse relationship between the number of responses required to increase the adjusting RI and the values of those stable titrated RIs, a similar relationship likely exists in the same manner for the number of responses required to decrease the adjusting RI. This is because, informally, the question TDMTS is asking is: “How high of a delay can you tolerate when you have to be this accurate?” For example, Experiment One of Kangas et al. (2010) arranged a TDMTS with titration parameters of two consecutive responses to increase the RI and an incorrect response to decrease the adjusting RI. When subjects were then exposed to an FR16 observing response requirement the adjusting RIs were approximately 18 s, 40 s, 20 s and 10 s. Subjects in Comparison 1, reported here, had an identical observing response requirement arranged under different TDMTS parameters of six consecutive correct responses to increase the RI and one incorrect to decrease the RI. The stable adjusted RI values for this condition were approximately 2 s, .1 s, and 5 s. When those same subjects were then exposed to a TDMTS schedule with titration parameters that required six consecutive correct responses to increase the adjusting RI and two consecutive incorrect responses to decrease the adjusting RIs increased, to approximately 6 s, 2 s, and 9 s. The increase in the incorrect response requirement, across the board depressed the subject’s performance compared to Experiment One in Kangas et al. (2010). It will be necessary to investigate what role the titration parameters play in the average stable RI that is likely to result, be it a “higher” value like Kangas et al. (2010) or a “lower” value reported here.

The results of this study do not suggest specifically which titration schedule may be the best or most effective to use. One of the things to be considered is whether or not a subject should be accurate at all the configurations at a specific delay. With a parameter that requires six consecutive correct responses to titrate the delay upwards and a stimulus array choices being made randomly-without-replacement with only four possible arrangements, it is very unlikely that a subject can increase the RI while having a persistent hue or side bias. Similarly, by increasing the requirement to decrease the adjusting RI a larger amount of stimulus control loss must occur before the RI will titrate downwards. If, as in Kangas et al. (2010), only two correct responses are required to increase the RI, then with the same four stimulus array configurations a subject could titrate the RI reliably with a persistent bias. Under any arrangement of the titration parameters for a TDMTS procedure, direct ratio of correct to incorrect, the variation utilized by Poling et al. (1996), or Wenger and colleagues (Wenger et al., 1990) the relationship between response accuracy and stable adjusted RI must be carefully considered. The best parameter arrangement is likely one where the RI cannot titrate with a persistent bias so such an effect cannot change the dependent variable.

A key limitation of this experiment is the lack of replication across conditions. Due to how little is known about the effects of various variables on performance under an arranged TDMTS the experiment was designed in an exploratory manner. This experiment was designed to test a wide variety of variables across a single set of subjects. This provided several advantages in the short term, 1) the single-subject design used here reduces the likelihood that individual differences between subjects could modify the results obtained, 2) repeated exposure to early conditions could have resulted in practice effects that would only manifest in later conditions (though without the necessary reversals, this could still be the case), and 3) we could quickly provide answers to several experimental questions in a short order. It will be important to extend these analyses with systematic replications and experiments.

Further investigations may be necessary to determine the usefulness of forgetting functions obtained from TDMTS data, and whether they are in line with similar conditions with DMTS. Brown and White (2005) discuss the maximum obtainable value for log d as approximately linear functions of the logarithm of the number of trials experienced. In TDMTS with performance dependent delays, the maximum obtainable log d value is not fixed across RI values. For this reason, a logit p analysis was utilized in this experiment because logit p is not subject to maximum obtainable value differences. An investigation of whether maximum obtainable value ceilings will render the combination of forgetting functions and TDMTS untenable is necessary.

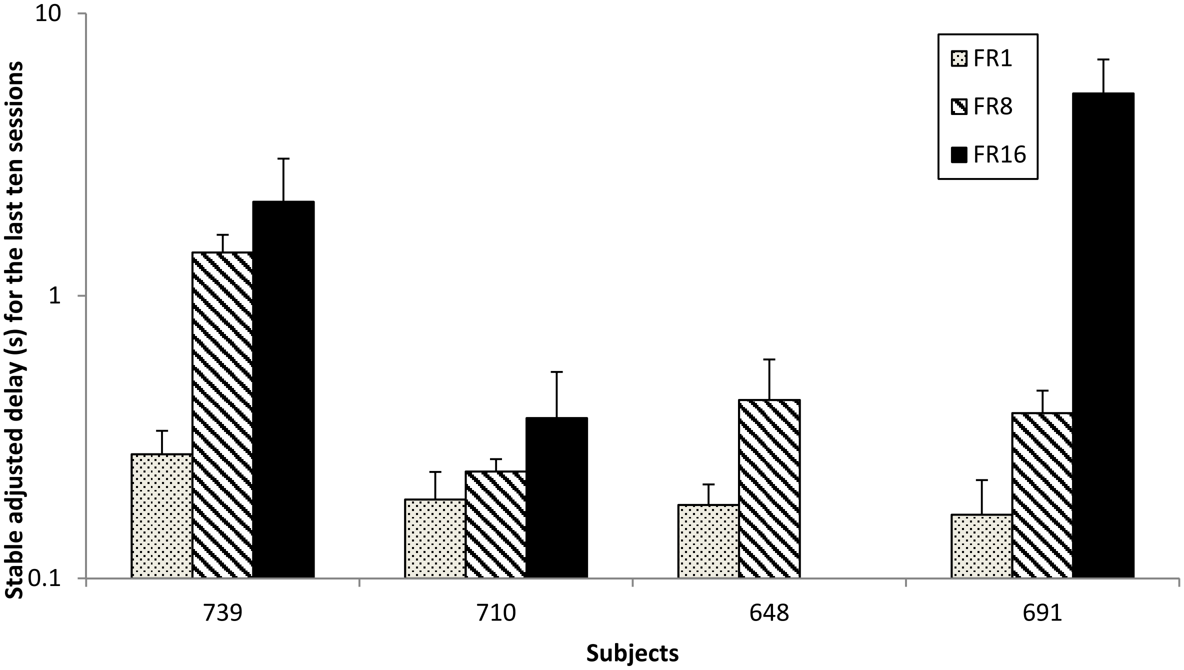

Figure 1. Stable adjusted retention intervals for Comparison 1. Figure 1 shows the adjusting RI for the last ten sessions in each condition of Comparison 1. The y-axis is adjusted RI value in seconds, the scale is logarithmic. The x-axis is grouped by subject, with the dotted bars being representing the FR1 conditions, the slashed bars representing the FR8 condition, and the solid bars representing the FR16. The error bars present one-standard deviation around the mean value.

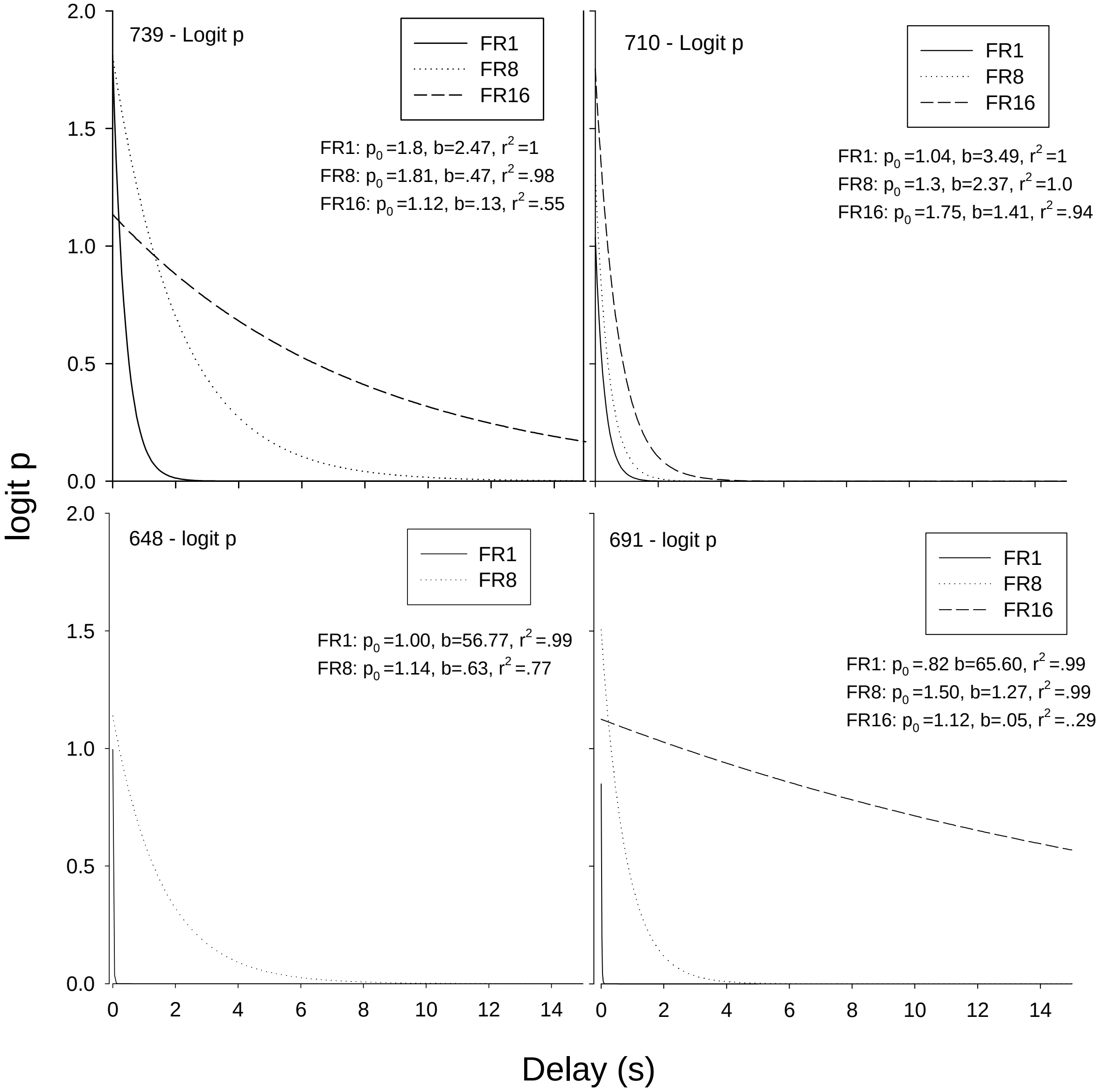

Figure 2. Logit p forgetting functions for Comparison 1. Figure 2 shows the obtained forgetting functions for all subjects for each condition in comparison 1. Values on the y-axis are logit p and values on the x-axis are RI values in seconds. Dashed lines represent the FR1 condition, dotted lines represent the FR8 condition, and solid lines represent the FR16 condition. p_0, b, and r^2 values for each subject by condition are below the subjects' respective legends.

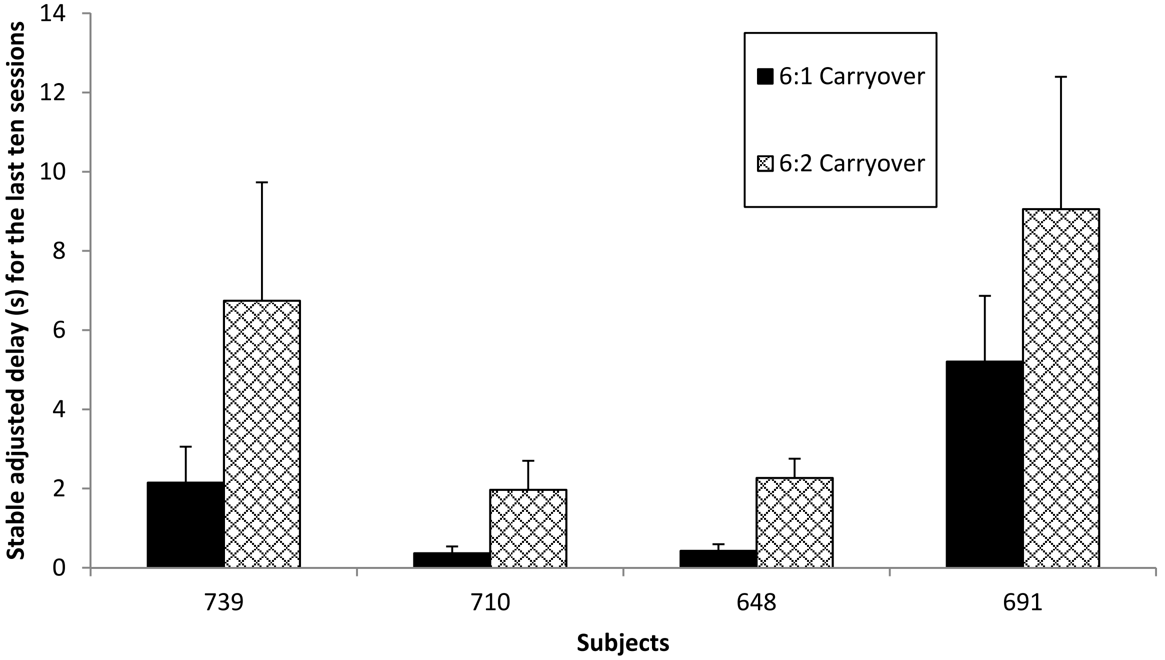

Figure 3. Stable adjusted retention intervals for Comparison 2. Figure 3 shows the adjusting RI for the last ten sessions in each condition of Comparison 2. The y-axis is average adjusted RI value in seconds. The x-axis is grouped by subject with solid bars as the 6:1 condition and the diagonal bars as the 6:2 condition. The error bars present one-standard deviation around the mean value.

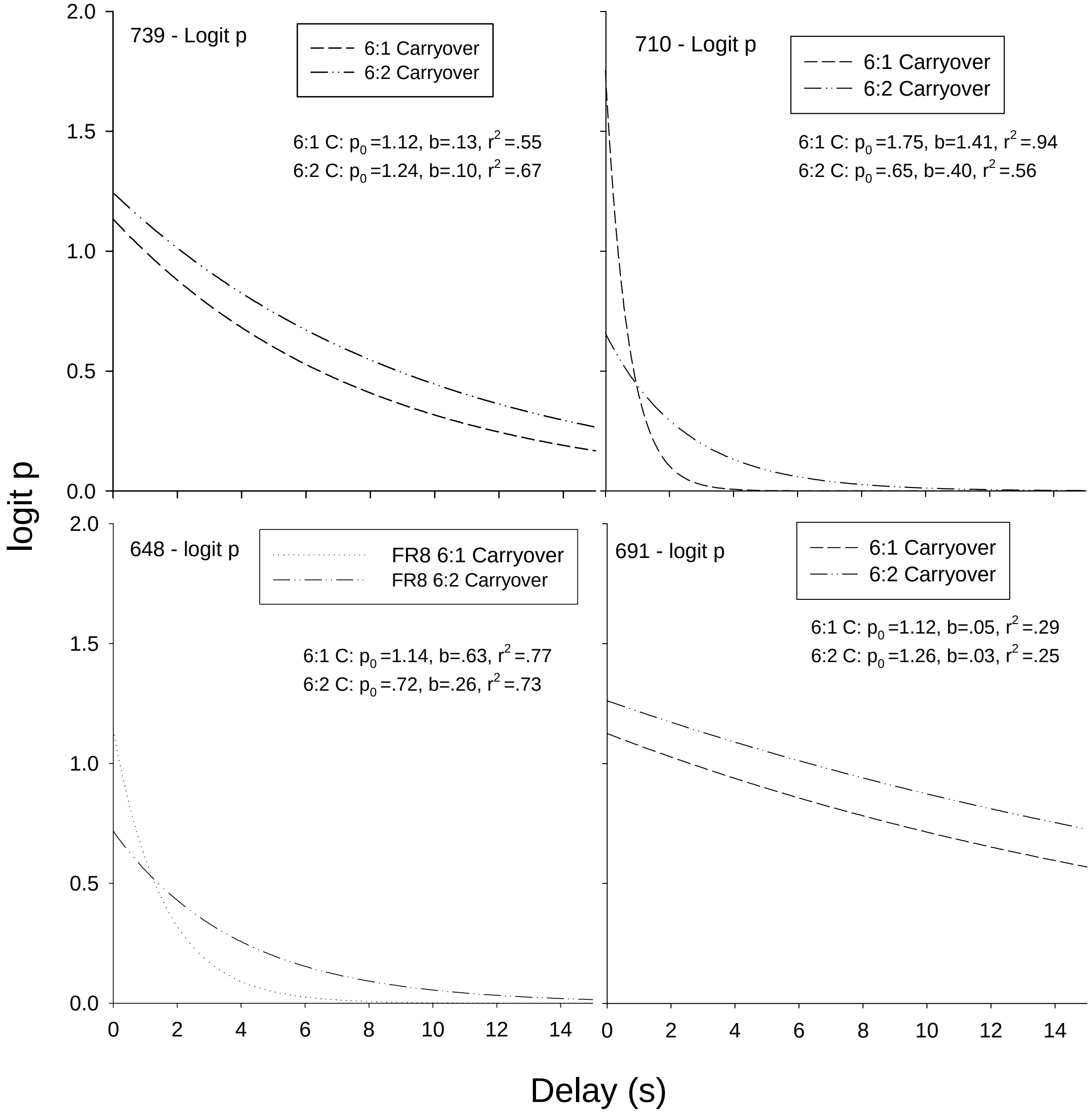

Figure 4. Logit p forgetting functions for Comparison 2. Figure 4 has the obtained forgetting functions for all subjects for both conditions in comparison 2. Values on the y-axis are logit p and values on the x-axis are RI values in seconds. Dashed lines are the 6:1 condition and dash-dot-dot lines are the 6:2 condition. p_0, b, and r^2 values for each subject by condition are below the subjects' respective legends.

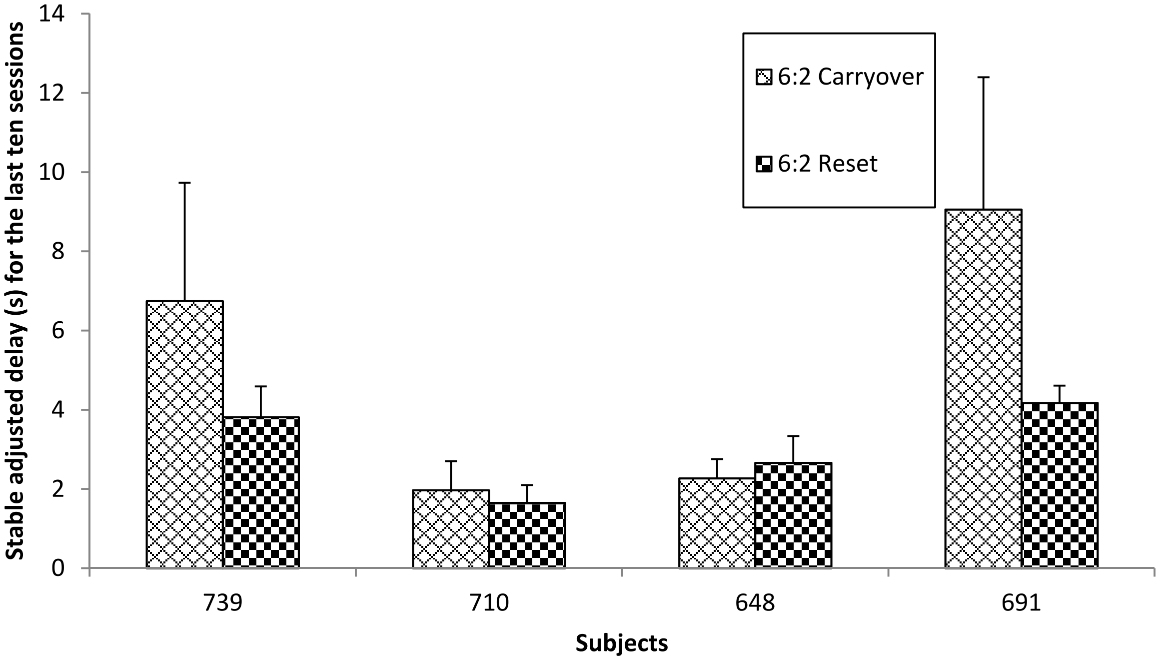

Figure 5. Stable adjusted retention intervals for Comparison 3. Figure 5 shows the average adjusting RI for the last ten sessions in each condition of comparison tree. The y-axis is the average adjusted RI value in seconds and the x-axis is grouped by subject with diagonal bars as the carryover condition and the checkered bars are the resetting condition. The error bars present one-standard deviation around the mean value.

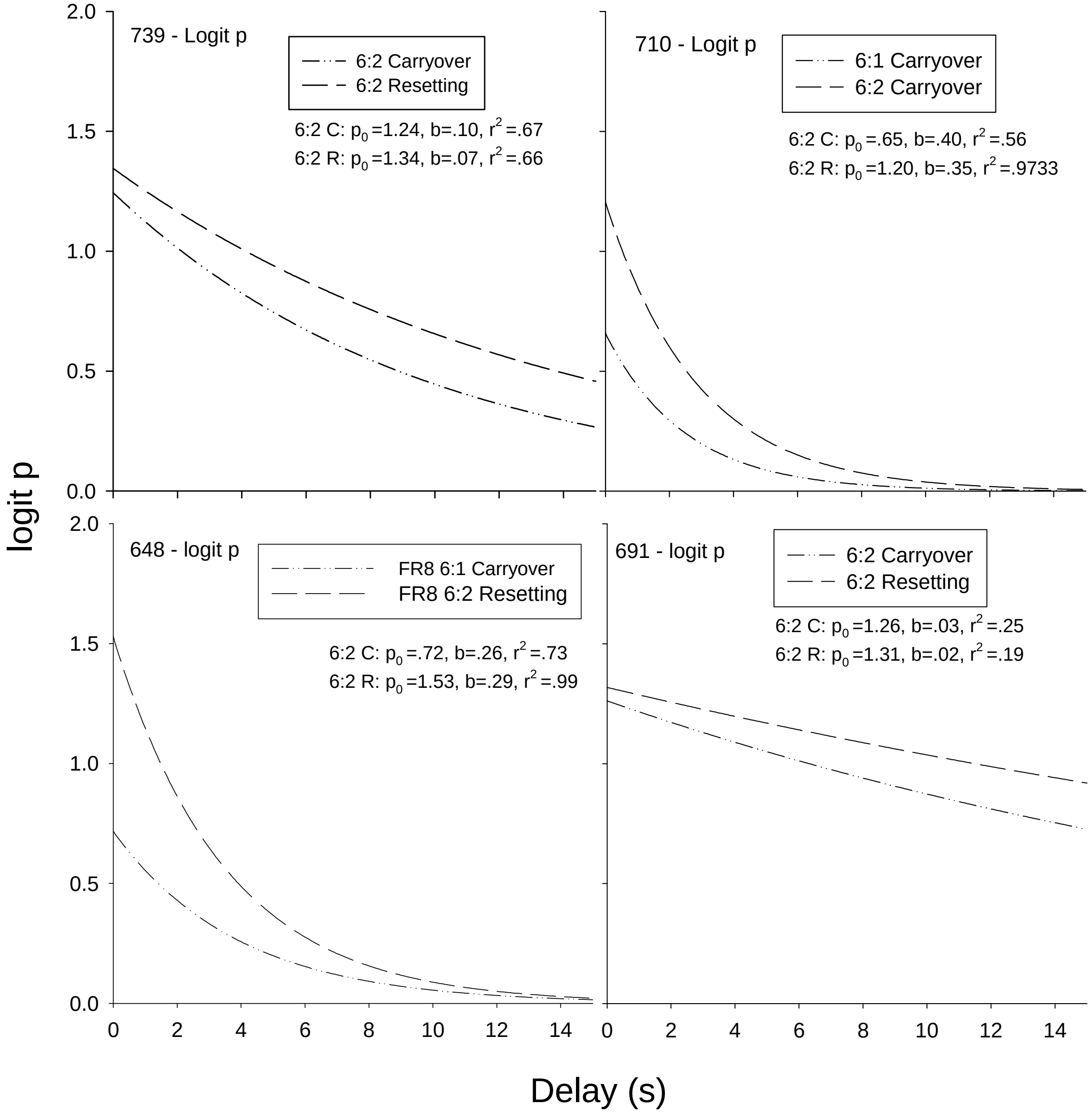

Figure 6. Logit p forgetting functions for Comparison 3. Figure 6 has the obtained forgetting functions for all subjects for both conditions in comparison 2. Values on the y-axis are logit p and values on the x-axis are RI values in seconds. Dash-dot-dot lines are the carryover condition and dashed lines are the resetting condition. p_0, b, and r^2 values for each subject by condition are below the subjects' respective legend.

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