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## Influence of the inter-reach-interval on motor learning

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**Abstract** Previous studies have demonstrated changes in motor memories with the passage of time on the order of hours. We sought to further this work by determining the influence that time on the order of seconds has on motor learning by changing the duration between successive reaches (inter-reach-interval (IRI)). Human subjects made reaching movements to visual targets while holding onto a robotic manipulandum that presented a viscous curl field. We tested four experimental groups that differed with respect to the IRI (0.5, 5, 10 or 20 s). The 0.5 s IRI group performed significantly worse with respect to a learning index than the other groups over the first set of 192 reaches. Each group demonstrated significant learning during the first set. There was no significant difference with respect to the learning index between the 5, 10 and 20 s IRI groups. During the second and third set of 192 reaches the 0.5 s IRI group's performance became indistinguishable from the other groups indicating that with continued training the initial deficit in performance could be overcome.

**Keywords** Motor learning · Time · Massed · Spaced · Interval · Reaching

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### Introduction

While making reaching movements, we are able to incorporate new experiences into our neural repertoire observed as changes in motor performance. Important to our understanding of motor learning is elucidating the influence that time has on both learning and recall of

motor memories. We can break up time's influence on the process of motor learning into different length scales such as seconds, hours, days or even years. Previous work has proven fruitful in the range of hours, however, less is known about how short time intervals on the scale of seconds could affect motor learning.

In previous work it has been shown that time plays a role in motor memory preservation and the ability to learn multiple internal models (Shadmehr and Brashers-Krug 1997), where an internal model holds the information necessary to take a movement's goal, such as reaching a target location, and implement the appropriate forces needed to accomplish this. It has also been shown that the neural activity presumed to represent the internal model moves from one set of brain regions to another within 6 h of experiencing such a force field (Shadmehr and Holcomb 1997).

We wished to determine the influence time has on the order of seconds. We hypothesized that if one takes less time between movements they should obtain a higher level of performance sooner than if they waited between movements. In this report, we present the results from an experiment in which four groups of subjects made reaching movements while experiencing a viscous curl force field identical to that used in the aforementioned studies. It is important that we use a similar paradigm as researchers have determined that task specific variables such as position of the individual can determine if a massed vs spaced training schedule is best (Abrams and Grice 1976).

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### Methods

Thirty-six adult subjects (age range 20–52 years, mean 27 years) consented to the experiment where they held onto a robotic manipulandum (Shadmehr and Mussa-Ivaldi 1994) while performing a center out reaching task in the horizontal plane to one of eight pseudorandomly chosen targets presented every 45° along a fictive circle of radius 10 cm. A sling supported the subject's arm.

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Movement of the manipulandum caused movement of a cursor on a computer monitor mounted vertically in front of the subjects. Subjects were instructed to make 500 ms long movements, and were given feedback after each movement on maximum velocity and duration with the target exploding after a successful movement having a maximum velocity between 0.3 and 0.75 m/s and duration between 450 and 550 ms. Upon termination of a movement and visual feedback, the subject's arm was brought back to the center actively by the manipulandum, subjects naturally assisted their return to the starting position. A computer recorded position and velocity of the handle at 100 Hz.

Subjects first performed a target set, which consists of 192 movements (24 in each direction), with the manipulandum motors turned off (null phase) with a forced inter-reach-interval (IRI) of 0.5 s after which time the next target was presented. Subjects were instructed to make movements as soon as a target appeared, but that reaction time was not important. Following the null phase the manipulandum produced a viscous curl field (fielded phase) that applied forces at the handle linearly proportional to the instantaneous velocity of the handle and perpendicular to its velocity.

Four experimental groups, differing by the IRI (0.5, 5, 10 or 20 s) made reaches during the fielded phase. The amount of time between movements was on average 3 s more due to the reaching movement, feedback presentation and returning to the start position. Approximately every sixth movement (range 3–12) in the fielded phase was a catch trial (CT), a trial with the torque motors secretly turned off. As it took the IRI groups a different amount of time to finish each set, the longer the IRI was the fewer sets of movements they made as is evident in the results.

### Measurement of learning

We used a learning index to quantify the influence of the IRI. The perpendicular displacement PD taken at the maximum velocity point of movements was our error proxy (Donchin et al. 2003). We are working on the assumption that the subjects are constructing an internal representation of the force field, an internal model (Lackner and Dizio 1994; Shadmehr and Mussa-Ivaldi 1994; Conditt et al. 1997). Thus, we expected that as subjects make more movements in the force field their reaching trajectories will become less deviated as has been shown in the past (Lackner and Dizio 1994; Shadmehr and Mussa-Ivaldi 1994); additionally, CT trajectories will become increasingly deviated. The learning index is

$$LI = \frac{|\langle CT \rangle|}{|\langle CT \rangle| + |\langle F \rangle|}, \quad (1)$$

where  $|\langle CT \rangle|$  is the absolute value of the mean CT PDs for a given bin (see below) of movements, likewise  $|\langle F \rangle|$

for F trials (Donchin et al. 2002). At the beginning of an experiment subjects have small deviations during the CT trials and large deviations for the F trials, thus the LI is close to zero. As the subjects learn the force field their mean CT increase in absolute value while the F trials become less deviated leading to an LI that approaches 1. It is conceivable that the LI would grow due to a situation outside of that outlined above, however examination of our data indicates that CT and F trials change together as has been previously argued (Donchin et al. 2002, 2003).

### Measurement of endpoint impedance

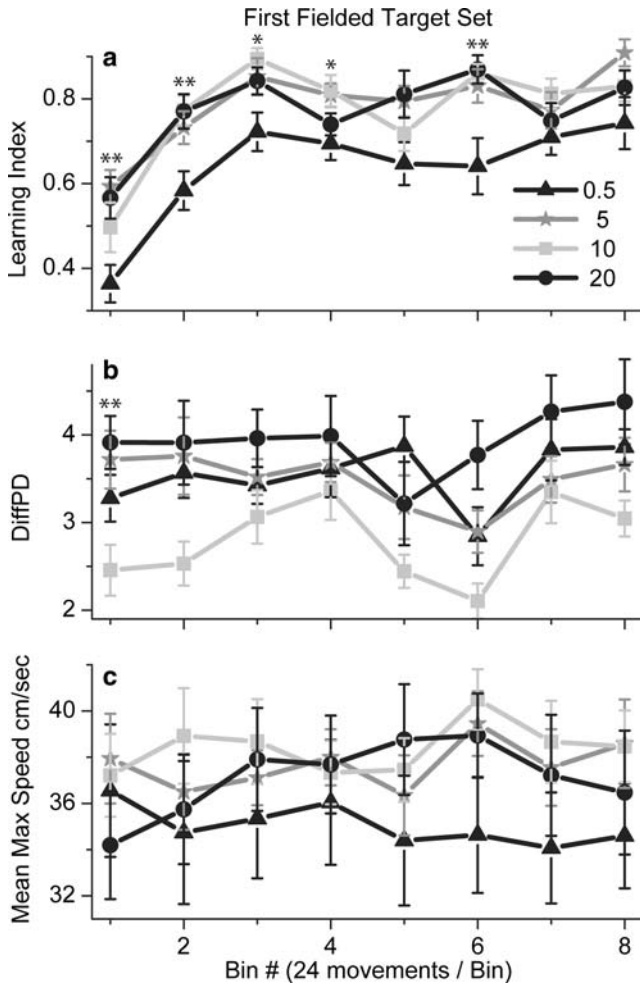
We measured the difference between the mean fielded PD for a given IRI group and the mean catch PD,

$$\text{DiffPD} = \frac{|\langle CT \rangle| - |\langle F \rangle|}{|\langle \text{Speed} \rangle|}, \quad (2)$$

where  $|\langle \text{Speed} \rangle|$  is the absolute value of the mean speed for both CT and F movements as there was no significant difference between them. All variables are taken at the maximum velocity point of the movement. As the force field magnitude is linearly proportional to the speed the DiffPD measures the amount of endpoint displacement per unit force. It should be noted that the speed did not differ significantly between the IRI groups and thus ignoring the denominator in Eq. 2 had no noticeable effect on the DiffPD results.

### Statistics

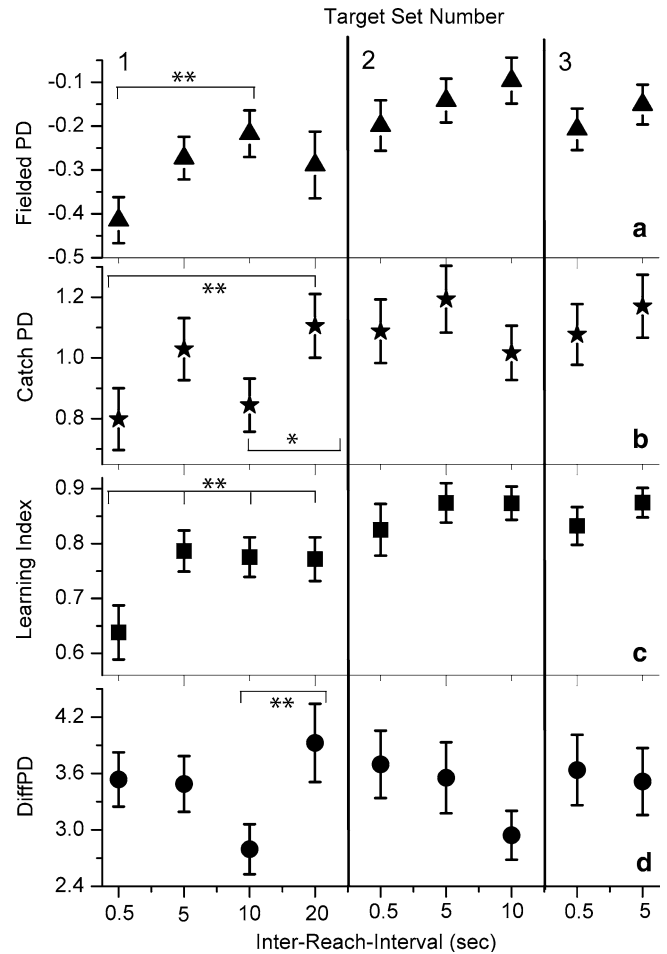
For each test statistic (LI, DiffPD, CT PD, etc.), we used bins of 24 consecutive movements and then split these movements up into the CT and F groups. We chose 24 movements as a compromise between having a fine enough temporal scale while assuring that there were enough CT within each bin. In general, there were 20 fielded movements and four CT per bin. Subsequently we re-calculated all statistics while forcing there to be 20 F and four CT movements per bin by including movements forward in time into our bin if necessary, no data point was used more than once, and results from this analysis did not differ significantly from the former, all results presented are from the latter design. For the results presented in Fig. 1, an ANOVA was carried out on the individual bins with IRI group as the main effect. For Fig. 2, an ANOVA with IRI group as the main effect and repeated measures on the bins variable (Statistica ANOVA with repeated measures) was used. A repeated measures design was also used to track changes over time. All ANOVAs were followed by Tukey's post hoc test. All experimental protocols were deemed acceptable by the IRB at Johns Hopkins University where the experiments were conducted.



**Fig. 1** a We have plotted the mean learning index  $\pm 1$  standard error of the mean for each group using bins made up from 24 consecutive movements (see “Methods” section). We have plotted an asterisk (\*) over bins that showed a significant difference between the IRI groups (ANOVA on individual bins with IRI group as main effect) with  $P < .05$ , and a double asterisk (\*\*) over bins with a  $P < .01$ . Each IRI group displayed a significant increase in the LI over the first target set (ANOVA on each individual group bins as main effect  $P < .01$ ). In panel (b) we have plotted the DiffPD for the same data used in (a). We found that there was only a significant difference between the groups for the first bin using the same ANOVA design used for the LI. In panel (c) we have plotted the mean maximum speed for the same data as in (a) and (b) with no significant differences seen

## Results

Each IRI group displayed a significant increase in the LI over the course of the first target set as seen in Fig. 1. (ANOVA, see methods,  $F = 5.94, 6.24, 10.94$  and  $5.372$ , respectively, starting with the 0.5 s group and all  $P$  values  $< .001$ .) The 0.5 s IRI group performed significantly worse than the other three groups during the first fielded set ( $F = 6.38$   $P < .01$ ). During the second and third target sets, the IRI groups became statistically indistinguishable (Set 2  $F = 0.8$ , set 3  $F = 1.77$ ). In Fig. 2 we have plotted the mean  $\pm$  one standard error of the



**Fig. 2** For each test statistic we have plotted the mean  $\pm$  one standard error of the mean for each IRI group for each target set that they participated in. We have used the same significance notation as that used in Fig. 1 with the addition of a bar joining the individual groups that are significantly different following Tukey’s post hoc test. For the LI in set one the 0.5 s IRI group was significantly different from all other IRI groups

mean for several test statistics, all significant differences were restricted to the first target set. Comparing the F PDs between groups we obtained an  $F = 4.28$ ,  $P = .012$ , and for the CT PDs an  $F = 5.34$ ,  $P < .01$  (see methods for ANOVA description). Each IRI group demonstrated the expected changes over the first target set, that is F PDs becoming smaller (all  $P$ s  $< .01$ ) and CT PDs becoming larger (all  $P$ s  $< .05$ ).

We wished to determine if the 0.5 s group had a lower LI due to an increase in endpoint mechanical impedance. If the subjects increased the degree of muscular co-contraction while making reaching movements they could make fairly straight reaches while the LI would be close to 0.5 (see Eq. 1). We compared the distance between the average F PD and the average CT PD for each of the groups calling this the DiffPD (see Eq. 2 methods). If the DiffPD is small it indicates a large amount of endpoint stiffness. It can be seen in Figs. 1b and 2d that the 10 s group had the highest level of endpoint stiffness

(ANOVA  $F=5.1$ ,  $P<.01$ ). We did not notice any trend in time for the DiffPD as we did with the LI and the other test statistics. Thus, it does not seem that a difference in impedance could explain the highly significant difference seen between the 0.5 s IRI group's LI and the other three groups for the first target set.

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## Discussion

Four groups of subjects held onto a robotic manipulandum while making reaching movements to eight targets waiting 0.5, 5, 10 or 20 s before presentation of the next target. We found that waiting less than 5 s between movements hampered early performance. While learning a novel motor task the neural controller must formulate an appropriate set of muscle contractions to achieve a goal, such as reaching a target location, which can be accomplished in several ways. First, one could formulate an inverse dynamics model that determines the forces needed to maintain the null phase kinematics, likewise one could increase the degree of muscular co-contraction, or endpoint impedance (Burdet et al. 2001; Osu et al. 2003), and finally one could incorporate both of the above models (Takahashi et al. 2001) transitioning from impedance control to inverse dynamics control as the internal representation of the force field becomes acceptable. Our results do not support the use of impedance control as we did not see any temporal trend in the DiffPD, unlike the LI which showed a significant increasing trend with time during the first target set. Thus, the subjects in this study appear to be using an inverse dynamics model over impedance control.

A possible explanation for our results is that the neural motor controller is limited in its ability to multi-task, and that planning the next movement uses some of the resources which would otherwise be incorporating the recent error information. It is also possible that the 0.5 s IRI group had some residual momentum in their arm musculature and tissue that acts as an added noise source that must be compensated for. In other words, the initial conditions of each reach for the 0.5 s group are more variable than for the other groups. It is possible that fatigue may have played a part in these results, however as the 0.5 s group's LI increased over time and became indistinguishable from the other groups fatigue is not likely the cause for the results presented here.

Recently we have published in abstract format results from a study in which each subject experienced all four of the IRIs used in this paper in a pseudorandom fashion (Huang et al. 2003). Results from this work also

pointed to a decrease in the amount of "learning" as the IRI decreased using a movement by movement analysis (Thoroughman and Shadmehr 2000; Donchin et al. 2003). By determining the time course of motor learning from seconds to hours and days we will come to a better understanding of this exceptional neuronal system, which may lead to a greater understanding of how different brain regions cooperate to form one of the most malleable neural systems possessed by all animals lending itself to evolutionary and architectural comparison.

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