and not velocities. In this sense, the visually in nature, they typically observe displacements
4.2.5 Non-Physical Visual Feedback Can Be Better
[19,13].
the relationship tends to be the most stable (see Section 2.3)
oscillator the fastest by moving the force-feedback de-
cussed in Section 4.2.1, the test subject could damp the
ci
difficulty because the task was especially di-
hard. As dis-
mulated skill $B(n, c)\hat{S}(n)$ (blue x’s) and estimated intrinsic
diculty $D(c)$ (black o’s)

each subject performed better with STRNG compared to MED and with MED compared to WEAK, implying that a stronger coupling spring $kc$, which helped keep the subject and the neural oscillator approximately in phase (recall Figures 6–8), promoted more effective coordination with the neural oscillator. Indeed, this was in agreement with motor resonance, and more specifically the theory of dynamic patterns, which suggested that the subject would coordinate with an external haptic-rate oscillator best when the dynamic pattern is stable, and prior experiments had showed that a 0° phase relationship tends to be the most stable (see Section 2.3) [19,13].

4.2.5 Non-Physical Visual Feedback Can Be Better
When humans watch passive objects vibrating mechanically in nature, they typically observe displacements
and not velocities. In this sense, the $NF-HINT$ model could be thought of as non-physical because the movement of the ball represented the oscillator’s negative velocity and not its position. Hence, at first consideration, one might assume that test subjects would have had relatively little success at interacting with the non-physical model. However, the situation required further consideration because the task was especially difficult. As discussed in Section 4.2.1, the test subject could damp the oscillator the fastest by moving the force-feedback device 90° behind the position of the oscillator, which is an unstable pattern according to the theory of dynamic patterns (see Section 2.3).

On a statistically significant level, subjects performed the task of stopping the oscillator more successfully when the negative velocity of the ball was plotted on the screen (compare $NF-HINT$ and $NF$ in Figure 9). We believe subjects performed more successfully because the ball provided them with a strategy—they were taught in the training phase to “follow the green ball.” Furthermore, they could then follow the green ball with a 0° phase lag, which is much more stable from the dynamic patterns perspective.

This result also showed that a theory from visual-only human coordination experiments could be extended to situations involving also auditory feedback: non-physical visual feedback could enable a subject to complete an otherwise impossible or very difficult task, if the visualization revealed an inner state or otherwise unseen strategy that provided a human test subject with assistance [18]. Indeed, some subjects commented that they could not really understand what they were doing, but they nonetheless performed successfully with $NF-HINT$.

4.2.6 Benefit of Appropriate Force Feedback
As suggested by Figure 9, subjects may have exhibited a tendency to perform worse with weak force-feedback (WEAK) in comparison with no force-feedback at all (NO-FF).

Although this effect was not determined to be statistically significant, this possibility could be investigated further in future work with larger numbers of participants. We note that weak force-feedback could possibly distract the subject from successfully employing a certain strategy, in particular due to the 90° phase relationship. Force-feedback may not be beneficial in all situations.

However, the medium strength (MED) and strong (STRNG) force-feedback models produced statistically significant improvements over the basic no force-feedback model (NF), and (STRNG) even over (NF-HINT), in which a strategy was explicitly provided to the test subject. This result strongly underscores the utility of incorporating force-feedback into systems that implement human interaction with virtual dynamical systems.

4.2.7 Perspective
Subjects were asked to fill out a questionnaire to describe their experience. Since the subjects had been instructed to attempt to follow the green ball for $NF-HINT$ during the training phase, they initially gained some intuition into the difficulty and dynamics of the task. The subjects all reported that they attempted to follow the green ball for the $NF-HINT$ model during testing (see the relatively low numbers of bounces in the $NF-HINT$ column of Table 1). However, the green ball was not present for the other four models. Many of the subjects adapted this strategy more or less successfully for the NF, WEAK, and even MED models. For example, subject # 5 even reported attempting to imagine where the green ball would have been in order to produce mental guidance for stopping the oscillator for NF.

Other subjects reported “incorrect” strategies, particularly for NF, such as keeping the force-feedback device 180° out-of-phase with the position of the Large oscillator. This strategy, if implemented perfectly, would not have damped the Large oscillator’s motion. In fact, participants would commonly move the force-feedback device slightly fewer than 180° (instead of an optimal