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Anticipatory phase correction in sensorimotor synchronization

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ABSTRACT

Studies of phase correction in sensorimotor synchronization often introduce timing perturbations that are unpredictable with regard to direction, magnitude, and position in the stimulus sequence. If participants knew any or all of these parameters in advance, would they be able to anticipate perturbations and thus regain synchrony more quickly? In Experiment 1, we asked musically trained participants to tap in synchrony with short isochronous tone sequences containing a phase shift (PS) of −100, −40, 40, or 100 ms and provided advance information about its direction, position, or both (but not about its magnitude). The first two conditions had little effect, but in the third condition participants shifted their tap in anticipation of the PS, though only by about ±40 ms on average. The phase correction response to the residual PS was also enhanced. In Experiment 2, we provided complete advance information about PSs of various magnitudes either at the time of the immediately preceding tone ("late") or at the time of the tone one position back ("early") while also varying sequence tempo. Anticipatory phase correction was generally conservative and was impeded by fast tempo in the "late" condition. At fast tempi in both conditions, advancing a tap was more difficult than delaying a tap. The results indicate that temporal constraints on anticipatory phase correction resemble those on reactive phase correction. While the latter is usually automatic, this study shows that phase correction can also be controlled consciously for anticipatory purposes.

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1. Introduction

Studies of *phase correction*—the process that maintains synchrony between a rhythmic movement such as finger tapping and an external rhythmic sequence when synchronization is intended—often use a perturbation method (Michon, 1967; Repp, 2005). The type of perturbation most appropriate for that purpose is the *phase shift* (PS), essentially the shortening or lengthening of a single interval in a (typically isochronous) pacing sequence, with the consequence that all subsequent sequence events are either advanced or delayed. Although phase correction naturally occurs also in the absence of perturbations (see, e.g., Vorberg & Schulze, 2002), the perturbation method enables the researcher to observe the process under a magnifying glass, so to speak. The *phase correction response* (PCR) to a PS (i.e., the shift of the next tap relative to its expected time in the absence of a PS) is quick, starting about 100 ms after the first phase-shifted event and evolving to full magnitude within about 300 ms (Repp, 2011a), and usually compensates for a substantial proportion of the PS, if not more (Repp, 2011b).

If PS direction and magnitude are varied in an experiment, as is usually the case, then linear regression of PCRs onto PSs yields a *PCR function* whose slope is an index of the effectiveness of phase correction. The slope expresses PCR magnitude as a fixed proportion of PS magnitude; this proportion is also referred to as alpha (the phase correction parameter in a linear model; Vorberg & Schulze, 2002) or as *mean PCR* (usually multiplied by 100 in that case to yield a percentage). The PCR function is typically quite linear if PS magnitudes stay within ±10% of the sequence inter-onset interval (IOI) duration, but its slope tends to decrease for larger perturbations, which means the complete function for PSs between ±50% of the IOI is sigmoid-shaped (Repp, 2002b, 2011b). The slope increases rapidly with IOI duration (i.e., as sequence tempo decreases) in 1:1 synchronization (Pressing, 1998; Repp, 2008) and continues to increase more gradually for IOIs beyond 1 s, where overcorrection of small PSs is observed (Repp, 2011b).[1]

Perturbations are typically introduced in a way that makes them difficult to predict. Thus, the direction (negative = interval shortening, a phase advance; positive = interval lengthening, a phase delay) and magnitude of a particular PS are usually chosen randomly from a set of discrete values, and the position of the PS in the sequence is also randomly chosen from a set of limited possibilities. This is done to avoid any possible adjustment of tap timing in anticipation of the perturbation, because this would reduce the PCR that is of interest. The aim is generally to study phase correction as a purely reactive process. However, people's ability to anticipate perturbations by adjusting their movement timing under conditions of reduced uncertainty is of interest in itself. This *anticipatory phase correction* (APC) is the subject of the present study.

Why might APC be of interest? For one thing, it brings phase correction under conscious control. The PCR is largely automatic, although it can be suppressed voluntarily to some extent by trying not to react to perturbations (Repp, 2002a; Repp & Keller, 2004). Mates (1994) distinguished two error correction processes in sensorimotor synchronization, phase correction and period correction, the latter being a response to a perceived tempo change and differing from phase correction in that it is largely under conscious control (Repp & Keller, 2004). Although a PS can be regarded as a local change in sequence tempo, it is generally assumed not to elicit period correction, though it can do so when PSs occur in random alternation with real (i.e., persistent) tempo changes (Repp & Keller, 2006). Repp (2002c) hypothesized that period correction might be the mechanism governing anticipation of another player's expressive timing in musical ensemble performance. If only period correction can be under conscious control, then APC would have to be an instance of period rather than phase correction. In that case, one might expect its effect to spill over into the next inter-tap interval, resulting in poor synchronization of the following tap. This is so because period correction changes the internal timekeeper or oscillator period underlying the tap timing whereas the pacing sequence continues at its original tempo following the PS. However, it seems plausible that phase correction also could be consciously controlled when that is necessary, only that such control is not normally exercised in connection with the PCR because automatic control is already highly effective. If APC is

[1] Recent research (Repp, Keller, & Jacoby, in press) has shown that the gain of phase correction (alpha) is temporarily boosted during the PCR.

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due to consciously controlled phase correction (an assumption already implicit in the term APC), its effect on inter-tap interval durations should be as local as that of the PCR, resulting in good synchronization of the following tap.

Another question of interest with regard to APC is whether it is affected by sequence IOI duration (tightly correlated with tapping rate in 1:1 synchronization) in the same way that this variable affects the PCR. The mean PCR increases with IOI duration, and it is larger for positive than for negative PSs, especially when PSs are large (Repp, 2011b). Will this also be true for APC? In other words, are the temporal constraints similar for APC and the PCR?

When some but not all information about an upcoming PS is available, the question arises whether any benefits can be derived from limited information. For example, when the magnitude of a PS is not known in advance, but its direction and position are known, how large will APC be? When only the position of a PS is known, will there be any APC at all (based perhaps on the most recently experienced PS), and will there be any benefit for the subsequent PCR? In general, if APC is smaller than the PS, there will be a *residual PS* followed by a PCR of the next tap. Is the mean PCR to a residual PS different from the PCR to an unanticipated PS?

We know of no previous studies that investigated APC directly, but there are some in which uncertainty about perturbations was reduced for one reason or another. For example, Praamstra, Turgeon, Hesse, Wing, and Perryer (2003) employed a paradigm, following Repp (2000), in which a PS of fixed direction and magnitude occurred repeatedly in each trial at fixed distances, namely every 10th interval. Only the position of the first PS in each trial was randomly chosen. Participants thus potentially had complete information about subsequent PSs. It appears, however, that participants did not track the position information, which was not pointed out in the instructions and would have required grouping or counting sequence events by fives, which does not come naturally (cf. Repp, 2007). Thus, participants effectively had only direction and magnitude information, obtained from listening (if the PSs were large enough to be perceived consciously). Praamstra et al. found that the baseline asynchrony between taps and tones shifted slightly in the direction of the PSs in the course of each trial. Because each PS created a local shift of asynchronies in the opposite direction (asynchrony = time of tap minus time of tone), the baseline shift resulted in almost equal mean asynchronies for trials containing positive PSs and trials containing negative PSs. This seemed to be an adaptive response of some sort, but there was no evidence of APC, which would have resulted in reduced asynchronies at the PS points.

APC could be said to occur when phase perturbations are applied repeatedly in a predictable pattern and participants learn to anticipate that pattern with their taps. For example, Stephan et al. (2001), following Thaut, Tian, and Azimi-Sadjadi (1998), used "cosine-wave modulated" metronome sequences in which IOIs occurred in a repeating short-long-long-short sequence. When the difference between short and long IOIs was small and difficult to perceive, participants' inter-tap intervals mimicked the IOIs at a lag of one. This kind of automatic tracking is a predictable consequence of continuous reactive phase correction (Repp, 2002c; Schulze, 1992).[2] However, when the difference between IOIs was larger, participants began to anticipate the changes, so that the patterns of IOIs and inter-tap intervals more or less coincided. In that condition, then, participants basically synchronized with a *rhythm* they had learned. Ultimately, synchronization with any learned non-isochronous rhythm could be regarded as an instance of continuous APC, but this generalization may not be appropriate because rhythm production requires the preparation and execution of more than one interval duration, hence a continuous switching or nesting of "periods", which is not really a corrective process at all. Indeed, ordinary reactive phase correction can be shown to operate in response to PSs within such a rhythmic context (Repp, London, & Keller, 2008), and perhaps APC would operate as well.

The notion of APC is intended to apply mainly to anticipation of single changes in timing about which advance information is provided, which we investigate here in the simple context of

[2] This process could also explain the "strong anticipation" described recently by researchers taking a dynamical systems perspective (Stephen & Dixon, 2011; Stephen, Stepp, Dixon, & Turvey, 2008; Stepp & Turvey, 2010). Stephen et al. found that synchronization with an unpredictably (chaotically) timed sequence resulted in tap sequences that exhibited similarly chaotic timing. This was attributed to learning and anticipation of fractal characteristics of the sequence, but it could well have been due simply to automatic PCRs. Note that in that task no specific information about upcoming perturbations was provided; therefore, APC as defined here could not have been involved.

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synchronization with an isochronous sequence. We report two experiments. In Experiment 1, we introduced PSs of two possible absolute magnitudes in short sequences and provided advance information about their direction, their position, both, or neither. We expected that information about direction or position alone would be of little help, but that information about both would lead to APC, even though the magnitude of the PS remained uncertain. The questions of interest were by how much participants would anticipate, whether the PS in the preceding trial would have any influence on APC, and whether the PCR to the residual PS would be enhanced relative to the no-information baseline condition. In Experiment 2, we provided complete advance information (i.e., including magnitude) and varied whether it occurred early or late relative to each PS. We also varied sequence tempo. The main questions of interest in Experiment 2, analogous to those asked about the PCR in previous studies, were what the temporal constraints on APC are, how APC changes with IOI duration, and whether it varies linearly or non-linearly with PS magnitude.

2. Experiment 1

2.1. Methods

2.1.1. Participants

The 11 participants included 8 graduate students and one postgraduate of the Yale School of Music (5 men, 4 women, ages 22–26), who were paid for their efforts, and both authors (ages 65 and 20, respectively). The musicians were regular participants in synchronization and perception experiments in author BHR's lab. Their primary musical instruments were piano (2), violin (3), viola, cello, oboe, and bassoon, which they had studied for 13–21 years. The authors are both amateur musicians with 10 years of lessons (BHR: piano; GPM: French horn, trumpet, guitar).

2.1.2. Materials and equipment

Each trial consisted of a sequence of 11–15 identical digital piano tones (C4 = 262 Hz, 40 ms nominal duration) with constant IOIs of 500 ms, except when a PS occurred. The PS could occur in one of five positions (tones 8–12), which means the preceding IOI was either shortened or lengthened. A PS was followed by three additional tones, hence the variable length of the sequences. The PS could have one of four magnitudes: −100, −40, 40, or 100 ms. Combination of five positions with four PS magnitudes resulted in 20 different trials. Four additional trials not containing any PS were included in two of the four experimental conditions (the ones providing position information).

The experiment was controlled by a customized program written in Max/MSP 4.0.9 running on an Intel iMac computer. The computer was connected to a Roland RD-250s digital piano that produced the tones, and participants listened over Sennheiser HD 280 pro headphones at a comfortable intensity while tapping with their preferred hand on a Roland SPD-6 electronic percussion pad that was held on the lap. The taps were recorded by the Max/MSP program and were saved as text files for later analysis.

2.1.3. Procedure

There were four conditions that were presented in a single 1-hour session in counterbalanced order according to an incomplete Latin square. Each condition comprised three blocks of 20 or 24 trials each. Participants sat in front of the computer and started each trial by pressing the space bar. In Condition 1 (no information), participants simply tapped with the tones in each trial, starting with the third tone, and tried to stay in synchrony throughout, adjusting to any deviation from regularity that might occur. In Condition 2 (direction information), an arrow pointing to the left or right appeared on the screen at the beginning of each trial and remained in view throughout the trial. Participants were told that a left-pointing arrow indicated that one tone would occur earlier than expected (i.e., a negative PS), whereas a right-pointing arrow indicated that one tone would occur later than expected (i.e., a positive PS).[3] In Condition 3 (position information), the tone immediately preceding the PS had a higher pitch

[3] Although, strictly speaking, all tones following a PS are shifted, subjectively only the first shifted tone appears to be early or late.

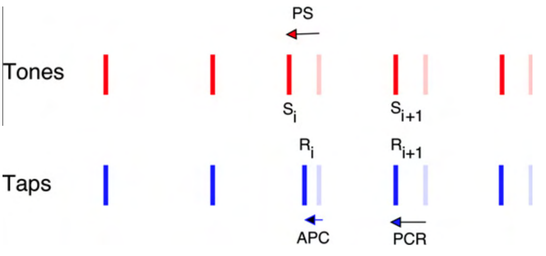

Fig. 1. Schematic diagram of a negative phase shift (PS) in the tone sequence as well as of *anticipatory phase correction* (APC), if any, and the *phase correction response* (PCR) in the participant's taps. Critical tone stimuli (S_i, S_{i+1}) and tap responses (R_i, R_{i+1}) are indicated. Pale-colored bars indicate where tones and taps would have occurred in the absence of a phase shift. For simplicity, timing variability is omitted, A = 0, and C = 0. As shown, $A_i = -PS/2$, $A_{i+1} = 0$, APC = PS/2, RPS = PS/2, and PCR = PS/2 (see text for definitions of variables). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(D4 = 294 Hz). Participants were informed that the tone following the higher tone would be shifted. The fact that there was no PS in four trials was not mentioned. In Condition 4 (direction and position information), both the arrow and the higher tone were present, and there were four trials without a PS. Participants were told that the PSs could vary in magnitude, and they were encouraged to make use of any advance information provided, if they could.

2.1.4. Analysis

Fig. 1 gives a graphic illustration of the following variables, which were computed per trial and then were averaged across repeated trials of the same type (first across different positions, then across blocks). The *asynchrony* A_i between the time R_i of the tap intended to coincide with the PS and the time S_i of the PS (or of a tone in an analogous position in trials without PS) was computed as $A_i = R_i - S_i - C$, so that a negative asynchrony indicated that the tap preceded the tone. The constant C = 15 ms corrected for the combined electronic transmission delays of tap registration and tone production, estimated from previous acoustic measurements. APC was calculated as $APC = A_i - A + PS$, where A is the expected asynchrony in the absence of a PS. (Note that $E(A_i) = A - PS$ when APC = 0; for example, a phase shift of −100 ms increases the expected asynchrony by 100 ms because the tap is made to lag behind the early tone.) The expected asynchrony A for this computation was estimated as the mean asynchrony in the corresponding positions of all trials without a PS.[4] The *residual phase shift* (RPS) was defined as $RPS = PS - APC = A - A_i$. The *phase correction response* (PCR) to the PS was calculated as $PCR = A_{i+1} - A_i$, which is equivalent to $(R_{i+1} - R_i) - (S_{i+1} - S_i)$, the difference between the local response and stimulus intervals. Phase correction is complete if PCR = PS. APC reduces the absolute magnitude of the PCR because it makes the response interval more similar to the stimulus interval (see Fig. 1).

2.2. Results

Fig. 2A shows the mean asynchrony A_i as a function of PS magnitude in the four experimental conditions. The mean asynchrony in trials without PS (PS = 0) was −25 ms, a fairly typical value for musicians in a simple synchronization task. In three of the experimental conditions, A_i was a linear function of PS with a slope close to −1, as is expected in the absence of APC. However, in the condition that provided direction and position information, the function was decidedly nonlinear, indicating APC. PSs of ±40 ms seemed to be fully anticipated, as the mean asynchronies were similar to when there was no PS.

Fig. 2B shows APC as a function of PS magnitude and experimental conditions. It can be seen that, on average, participants anticipated the PSs by about ±40 ms, which corresponds to the magnitude of

[4] Alternative ways of calculating APC would have been $APC = A_i - A_{i-1} + PS$, $APC = (R_i - R_{i-1}) - (S_{i-1} - S_{i-2})$, or $APC = (R_i - R_{i-1}) - (R_{i-1} - R_{i-2})$.

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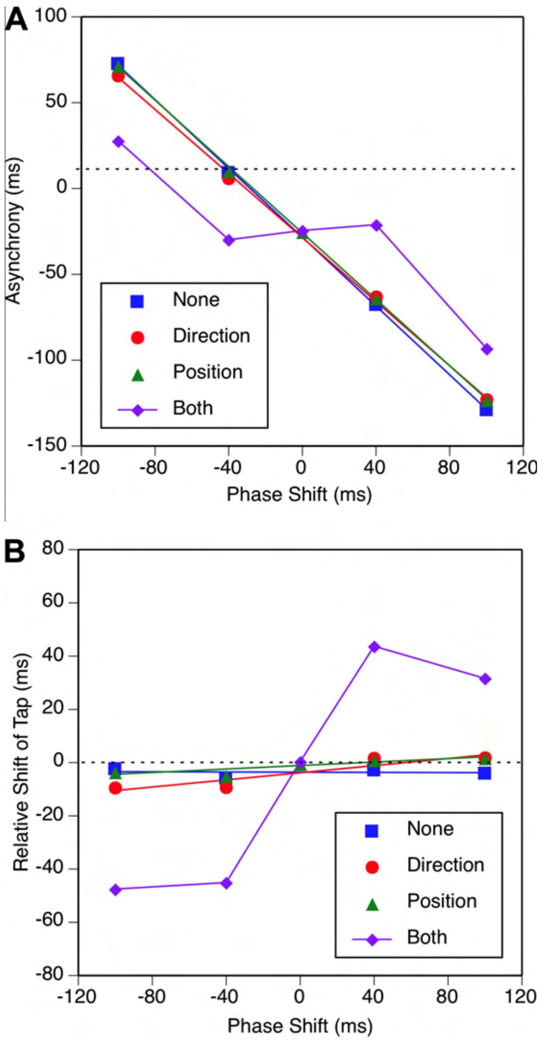

Fig. 2. (A) Mean asynchrony at the phase shift point and (B) mean anticipatory phase correction as a function of phase shift magnitude and experimental condition in Experiment 1.

the smaller PS. This indicates a conservative anticipatory strategy. In the condition without advance information, the APC function was completely flat, as expected, corresponding to a slope of −1 in Fig. 2A. In the conditions that provided direction or position information, the slope was slightly positive, slightly more so for direction than for position information, but there was hardly any APC to speak of.

Fig. 3A shows the PCR as a function of PS magnitude and experimental conditions. Here, too, highly linear functions can be seen in three conditions, albeit with a positive slope, as expected for the PCR. In the condition that provided direction and position information, the function was again very nonlinear. The almost perfect linearity in the other conditions is actually a little surprising because the larger PS amounted to ±20% of the interval duration, which might have been expected to elicit a smaller proportional PCR than the smaller PS of ±8% (Repp, 2002b, 2011b). However, there was no indication of any nonlinearity in these three functions. The nonlinearity of the fourth function was obviously due to the APC, which diminished the PCR.

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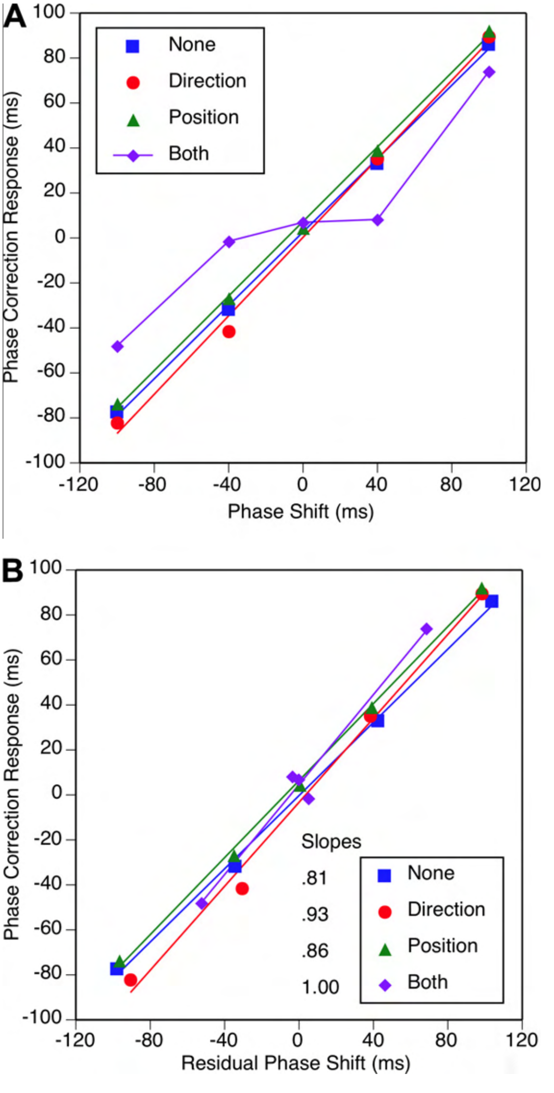

Fig. 3. Mean phase correction response as a function of (A) phase shift magnitude and (B) residual phase shift magnitude, in the four experimental conditions of Experiment 1.

Fig. 3B plots the PCR as a function of the residual PS. Now all four functions are strongly linear, the fourth function because three of the data points nearly coincide near RPS = 0, due to the almost complete APC for the smaller PSs. The four functions differ somewhat in slope, as indicated in the figure. The shallowest slope was obtained when no information was provided; position information increased the slope slightly; direction information increased it further; and both position and direction information yielded the steepest slope, indicating enhanced (on average, just perfect) reactive phase correction.

Individual slope values were submitted to a one-way ANOVA[5] that did not indicate a significant effect of condition, $F(3,30) = 3.01$, $p = .099$. However, an equivalent multivariate test did indicate a

[5] All ANOVAs reported in this paper were of the repeated-measures type, with the Greenhouse–Geisser correction routinely applied to effects with more than one degree of freedom.

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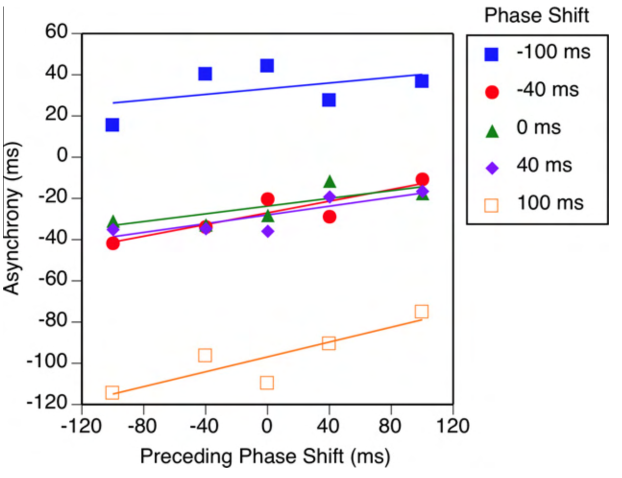

Fig. 4. Mean asynchrony at the phase shift point as a function of phase shift magnitudes in the current trial (legend) and in the preceding trial (*x*-axis) when position and direction information was provided (Experiment 1).

significant effect of condition, $F(3,8) = 7.65$, $p = .010$, and pairwise comparisons of conditions by means of *t*-tests also yielded significant results. In particular, the mean slope was significantly shallower in Condition 1 (no information, 0.81) than in Condition 2 (direction information, 0.95), $t(10) = 3.15$, $p = .010$, significantly shallower in Condition 3 (position information, 0.85) than in Condition 4 (direction and position information, 0.98), $t(10) = 3.88$, $p = .003$, and significantly shallower in Condition 1 than in Condition 4, $t(10) = 3.11$, $p = .011$.[6] These results indicate that direction information enhanced the PCR, whereas position information had little effect. There were also significant correlations between the individual slopes in Conditions 1 and 2, $r = .846$, $p = .001$, and in Conditions 3 and 4, $r = .851$, $p = .001$, but not between other pairs of conditions, with the correlation between Conditions 2 and 3 being particularly low, $r = .108$. This suggests that position information had some effect as well, but that this effect varied across individuals and did not result in an overall enhancement of the PCR.

To determine whether APC in Condition 4 was influenced by the magnitude of the PS in the preceding trial, Fig. 4 plots the asynchrony $A_i = APC + A - PS$ as a function of the PS magnitudes in the current and preceding trials. It is evident that, at each current PS magnitude, the preceding PS was positively correlated with APC (mean $r = .77$), though the effect was small. In other words, participants anticipated the current PS slightly more after experiencing a large PS than after experiencing a small PS. Even when there was no current PS, slight APC in the direction of the preceding PS occurred. Because this analysis was performed on the aggregate data of all participants in order to obtain sufficient numbers of observations for all sequential pairs of PS magnitudes, the reliability of these effects across participants could not be tested for significance.

2.3. Discussion

The results of this experiment confirm some predictions and answer some questions about APC. First, as predicted, information solely about the position of a PS had little effect on the PCR, which has the methodological implication that it is not essential to make the positions of perturbations unpredictable in synchronization experiments. Information solely about the direction of a PS did enhance the PCR, suggesting that advance knowledge of the direction in which a tap will have to be shifted facilitates that shift, even though it occurs rather automatically. As expected, however, only information about both position and direction enabled significant APC.

[6] The mean slopes differ slightly from the slopes of the functions fitted to the mean data (Fig. 3B).

APC was conservative on average, being approximately equal to the smaller of the two possible PS magnitudes in each direction (i.e., ±40 ms). This strategy was not optimal in terms of minimizing asynchronies; this would have required APC equal to the mean PS in each direction (i.e., ±70 ms). APC in either direction was somewhat larger if the PS in the preceding trial was large than when it was small, which suggests that memory plays some role in APC.

3. Experiment 2

In this experiment we investigated the accuracy and variability of APC when full advance information about PSs is given. One decision we had to make was in what form to provide this information. One possibility is to expose participants to a repeating PS of the same direction and magnitude in each trial, so they can rely on their memory of previous PSs to anticipate future PSs. However, if the PS is repeated periodically at relatively short intervals (e.g., every fourth position), then the task becomes rather similar to synchronization with a known rhythm, in which case it would not be quite appropriate to speak of APC. This could be avoided by presenting the PS at irregular intervals, with each position being cued (e.g., by a change in pitch, as in Experiment 1). Still, participants would have to rely on auditory memory, which might lead to a gradual improvement within each trial. While this is certainly a valid approach, we opted instead for a completely randomized presentation of PS magnitudes, directions, and positions, and provided advance information about all of these parameters by a visual analog display (a slider).

Across two separate sessions, we varied the time at which the slider moved to indicate an upcoming PS. The information was provided either "early", so that only the tap following the next tap needed to be shifted, or "late", in which case the next tap had to be shifted. In addition, we varied the sequence tempo (IOI duration). A relatively fast tempo was expected to impede a rapid change in movement planning, especially when the advance information was provided late, resulting in reduced and more variable APC. Such temporal constraints were not expected to play a role at slower tempi, but variability was expected to increase due to an increase in temporal uncertainty with IOI duration.

The general design of the experiment, including PS magnitudes and sequence tempi (baseline IOIs), was deliberately similar to that of a recent experiment in which the PCR to relatively large, unpredictable PSs was the focus (Repp, 2011b: Experiment 2). Thus, the present PCR with APC could be compared to the PCR without APC in that previous study. There the PCR had exhibited a pronounced asymmetry, being larger for positive than for negative PSs, especially when the tempo was fast. In other words, it was more difficult to advance than to delay a tap in response to large PSs. In addition, the mean PCR to positive PSs, at least, had increased with IOI duration, though it stopped short of overcorrection. We wondered whether APC, and the PCR to the residual PS, would exhibit a similar pattern.

3.1. Methods

3.1.1. Participants

The 10 participants included 9 graduate students from the Yale School of Music (3 men, 6 women, ages 22–27), who were paid for their efforts, and author BHR (age 66). The musicians were regular participants in synchronization and perception experiments in BHR's lab. Their primary musical instruments were piano (2), violin (1), viola (2), trombone (1), harp (1), and guitar (2), which they had studied for 10–24 years. Two of them and BHR had participated in Experiment 1.

3.1.2. Materials and equipment

The equipment was the same as in Experiment 1. Auditory sequences consisted of the tone C4 (262 Hz, 40 ms nominal duration) repeated at one of five tempi, corresponding to baseline IOIs of 400, 600, 800, 1000, or 1200 ms. Sequences were of variable length and much longer than in Experiment 1. Each trial contained 10 PSs that occurred at irregular intervals, with 4–7 unchanged IOIs intervening (this number varying randomly). The first PS could occur in the 9^{th}–12^{th} position. The 10 PSs had magnitudes ranging from −50% to 50% of the baseline IOI in steps of 10% (not including zero). Each PS magnitude occurred once in a trial, and their order was random.

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A horizontal slider within a rectangular frame 12 cm wide and 2.3 cm high was displayed on the computer screen in front of the participant. Its neutral position was in the center. To indicate an upcoming PS, the slider shifted leftward or rightward in proportion to the magnitude of the PS. A leftward shift of 3 cm indicated a PS of −50%, whereas a rightward shift of 3 cm indicated a PS of 50%. A 6-mm shift, which was clearly visible, corresponded to 10% of the IOI. Each shift occurred in synchrony with the tone preceding the PS in the "late" condition, and in synchrony with the penultimate tone preceding the PS in the "early" condition. The slider shifted back to the neutral position in synchrony with the PS in the "late" condition but in synchrony with the following tone in the "early" condition.[7]

3.1.3. Procedure

Participants came for two 1-hour sessions, typically one week apart, one for the "early" condition and the other for the "late" condition, in that order. Participants were asked to start tapping with the third tone in each trial and to stay in synchrony with the tones throughout. The slider was explained to them, and they were instructed to shift their next tap (in the "late" condition) or the tap following their next tap (in the "early" condition) in proportion to the shift of the slider. Because they could perceive large asynchronies between their shifted tap and the shifted tone, they effectively received immediate feedback about the success of their APC. Each session consisted of 8 blocks of 5 trials each. The trials represented the five tempi and occurred in random order. The first two blocks in each session were considered practice and were not analyzed.[8]

3.1.4. Analysis

Anticipatory phase correction in each trial was calculated here as APC = $A_i - A_{i-1}$ + PS. The APC values were converted to percentages of IOI duration, as were the PS magnitudes. APC percentages for the same PS were averaged across the six trial blocks, and their standard deviation across blocks was also calculated. APC percentages plotted as a function of PS magnitude yielded an APC function for each of the five IOI durations in each of the two conditions ("early", "late"). Averaged across participants, all of these 10 functions had strong linear trends, with R^2 values ranging from .954 to .993. Although there were nevertheless some significant deviations from linearity (see below), linear regression functions captured the major trends well. Their slopes indicated the effectiveness of APC (i.e., how much of a PS was corrected for, on average), whereas their intercepts indicated any asymmetry between APC for negative and positive PSs. Asymmetries were also assessed by fitting separate regression lines to the data points for negative and positive PSs and comparing their slopes.

The phase correction response, PCR = $A_{i+1} - A_i$, was examined as a function of the residual phase shift, RPS = PS − APC. These scatter plots (averaging across blocks was not possible here because of the continuously variable RPS values) also exhibited predominantly linear tendencies and were fitted with regression lines. Their slope was the measure of the mean PCR as a proportion of RPS, or phase correction effectiveness. In a few cases, outlier data points that seriously affected the slope of the regression line were deleted. The intercepts of the regression lines reflected asymmetries in the PCRs to negative and positive RPSs, which were also investigated by fitting separate regression lines to the data points for negative and positive RPSs and comparing their slopes.

3.2. Results

3.2.1. Anticipatory phase correction (APC)

The average APC functions for the two conditions and the five IOI durations are shown in Fig. 5. The fitted functions shown are third-order polynomials (i.e., cubic functions), because most functions deviated significantly from linearity. An overall 2 (conditions) × 5 (IOIs) × 11 (PSs) ANOVA was first conducted on participants' APC percentages. (To ensure equal spacing of PS magnitudes, the intercept

[7] This difference was not really intended and was discovered only after the data had been collected. However, it could not have affected APC because the critical tap had to be planned (and often executed) before the slider moved back to neutral.

[8] Due to a fault in the program, trials occasionally stopped after the first two tones. Participants were asked to jot down the IOI of such trials (which was displayed on the screen) and repeat the trials at the end of the session. Data from a total of three blocks were lost because they had not been saved correctly.

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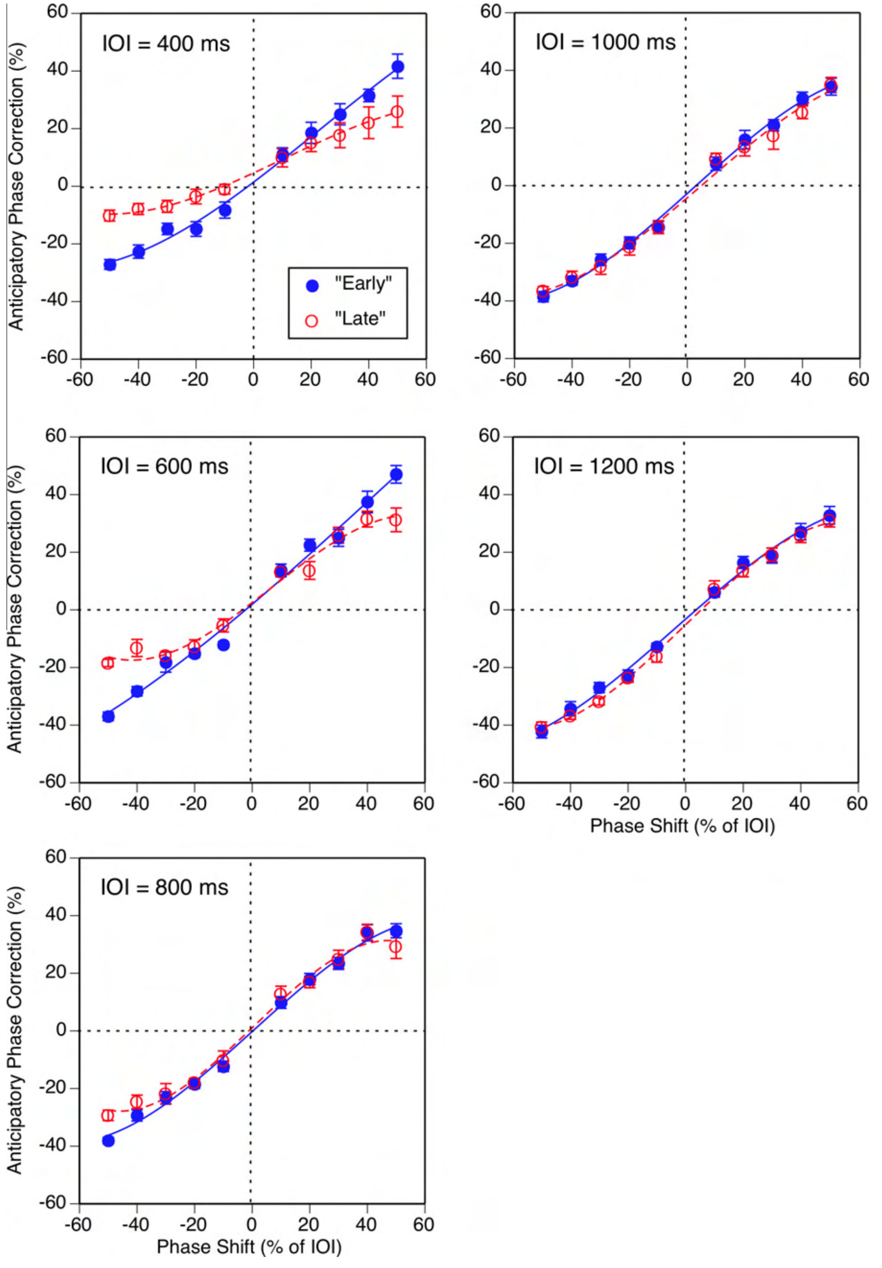

Fig. 5. Anticipatory phase correction in the "early" and "late" conditions of Experiment 2 as a function of phase shift magnitude, at each of five IOI durations. Error bars are ±1 standard error. Cubic functions have been fit to the data points.

values of linear regression fits to individual data were included for PS = 0.) The main effect of PS, which was obviously significant due to the strong linear trend, was decomposed into orthogonal polynomial contrasts. Four of these were significant in addition to the linear trend: the quadratic, $F(1,9) = 7.37$, $p = .024$, cubic, $F(1,9) = 26.30$, $p = .001$, fifth order, $F(1,9) = 13.54$, $p = .005$, and seventh order,

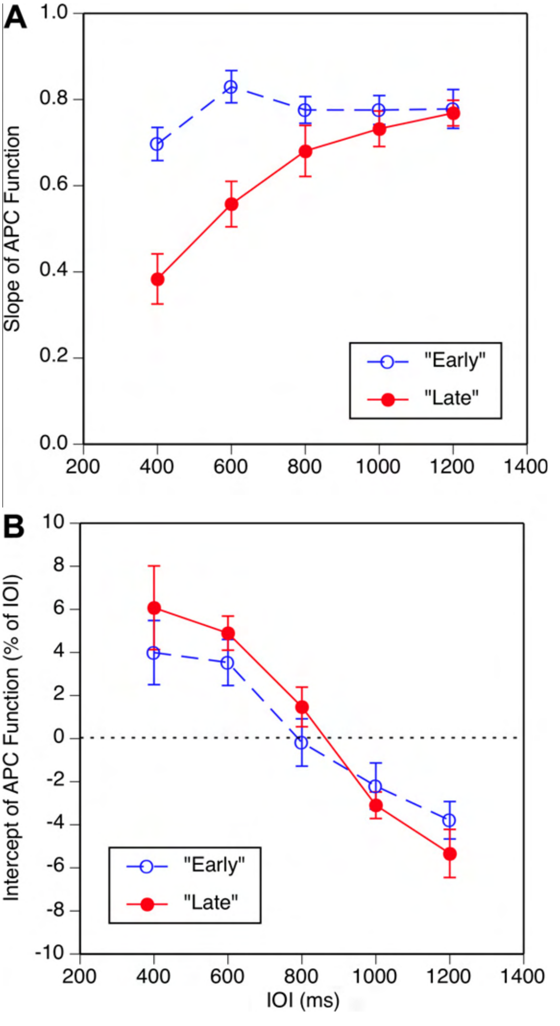

Fig. 6. Mean (A) slopes and (B) intercepts of APC functions as a function of condition and IOI in Experiment 2. Error bars are ±1 standard error.

$F(1,9) = 12.81$, $p = .006$. One-way ANOVAs with polynomial decomposition were subsequently conducted on each of the 10 APC functions. Of main interest were quadratic trends, which may reflect asymmetries in APC for negative and positive PSs, and cubic trends, which indicate differences in APC for small and large PSs. Higher-order trends were usually not significant for individual functions. (Their significance in the overall analysis probably reflects a general tendency for the slope of the function to be steeper between PSs of −10% and 10%.) A quadratic trend was significant for only one function ("early", IOI = 400 ms, $F(1,9) = 5.69$, $p = .041$), reflecting more effective APC for positive than for negative PSs. Six functions, however, showed significant cubic trends ("early": IOIs = 800, 1000, 1200 ms; "late": IOIs = 600, 800, 1200 ms, with F values ranging from 5.83 to 45.68, and p levels from .039 to < .001). All these functions were sigmoid-shaped (i.e., their cubic coefficients were negative), indicating that small PSs were more effectively anticipated than large PSs.

The overall ANOVA also revealed a significant main effect of IOI as well as interactions between Condition and IOI, Condition and PS, and between all three variables. The effects of condition and

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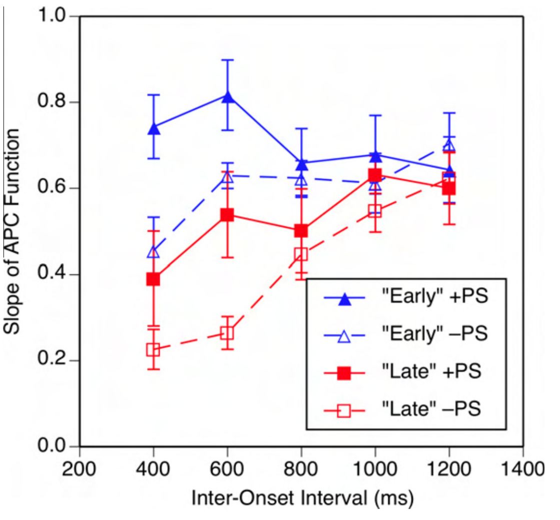

Fig. 7. Mean slopes of separate APC functions for positive and negative phase shifts as a function of condition and IOI in Experiment 2. Error bars are ±1 standard error.

IOI could be assessed more effectively in a 2 × 5 ANOVA on the slopes of linear regression lines fitted to participants' APC functions, whose mean values are shown in Fig. 6A. Here it can be seen that APC was larger in the "early" than in the "late" condition, $F(1,9) = 12.09$, $p = .007$, that APC increased with IOI duration, $F(4,36) = 21.88$, $p < .001$, and that this increase was much more pronounced in the "late" than in the "early" condition, $F(4,36) = 13.51$, $p < .001$. A separate one-way ANOVA on the "early" data revealed only a marginally significant effect of IOI, $F(4,36) = 3.36$, $p = .044$, which was evidently due to the increase between the two shortest IOIs. The figure further reveals that APC in the "early" and "late" conditions converged at longer IOIs but remained conservative, amounting to only about 80% of the PS on average.

Fig. 6B shows the mean intercepts of linear regression lines fitted to the APC functions, which were similar though not identical to the intercepts of the cubic functions shown in Fig. 5. In both conditions, the mean intercept was positive at short IOIs and changed to negative at long IOIs. The main effect of IOI was significant, $F(4,36) = 36.35$, $p < .001$, but its apparent interaction with condition was not reliable, $F(4,36) = 2.28$, $p = .122$. These results indicate (more clearly than did any quadratic trends in the APC functions) that participants tended to anticipate positive PSs more than negative PSs at short IOIs, and the opposite at long IOIs.

Another measure of such asymmetries was obtained by fitting separate regression lines to the APC functions for positive and negative PSs. Since each of these linear regressions was based on only five data points (each being an average of six APC observations), the slopes were somewhat variable but nevertheless showed a systematic pattern, which is graphed in Fig. 7. It should be noted, first, that theses slopes were generally shallower than those of the complete APC functions (Fig. 6A), which indicates a "step" (i.e., steeper slope) in the function between PSs of −10% and 10%, as already suggested by the higher-order nonlinear trends mentioned earlier. Second, slopes were shallower for negative than for positive PSs at the two fastest tempi, with little difference at the three slower tempi. A 2 (Conditions) × 2 (Direction) × 5 (IOIs) ANOVA confirmed main effects of condition, $F(1,9) = 15.34$, $p = .004$, and IOI, $F(4,36) = 7.03$, $p = .003$, as well as a Condition × IOI interaction, $F(4,36) = 3.33$, $p = .047$. In addition, however, the main effect of direction, $F(1,9) = 8.00$, $p = .020$, and the Direction × IOI interaction, $F(4,36) = 4.33$, $p = .016$, were significant, showing the just noted tempo-dependent asymmetry to be reliable across participants.

The variability (standard deviation across the six blocks) of APC (expressed as a percentage of IOI) is shown in Fig. 8 as a function of PS magnitude for the two conditions and five IOIs, with cubic curve fits.

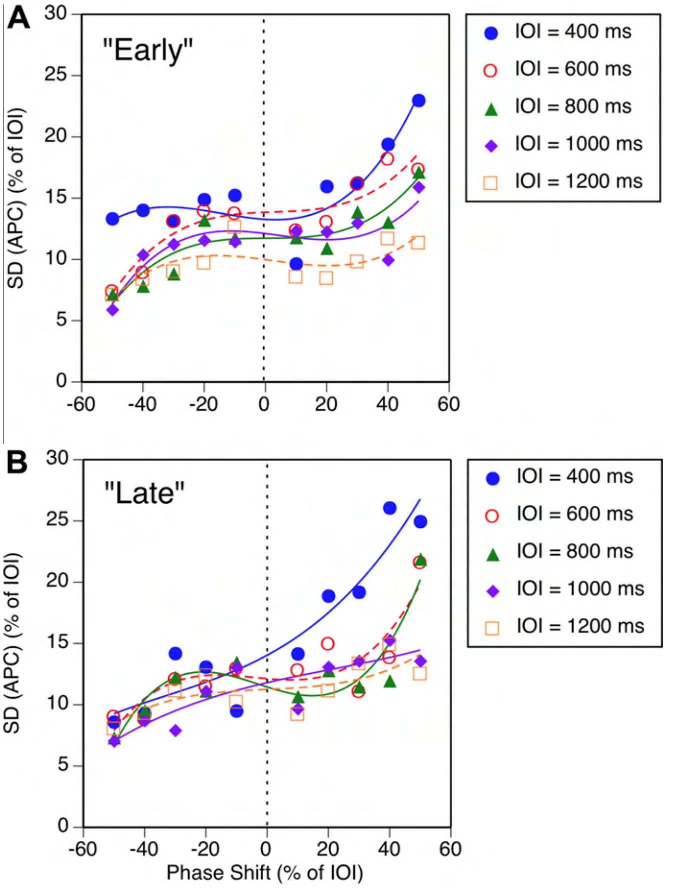

Fig. 8. Mean standard deviations of APC in the "early" and "late" conditions of Experiment 2 as a function of phase shift magnitude, at each of five IOI durations. Error bars are omitted. Cubic functions have been fit to the data points.

A 2 (conditions) × 5 (IOIs) × 10 (PSs) ANOVA was conducted on these values. (No data were inserted here for PS = 0.) A significant main effect of IOI, $F(4,36) = 22.19$, $p < .001$, unexpectedly reflected a *decrease* in variability as IOI increased; only the linear trend of that effect was significant, $F(1,9) = 52.77$, $p < .001$. There was also a significant main effect of PS, $F(9,81) = 20.53$, $p < .001$, of which both the linear and cubic trends were significant, $F(1,9) = 71.21$, $p < .001$, and $F(1,9) = 18.78$, $p = .002$, respectively. Variability was smallest for large negative PSs, largest for large positive PSs, and intermediate for PSs of −30% to 30%, where it changed relatively little. This pattern, which also had not been predicted, can be seen more clearly in the "early" condition (Fig. 8A) than in the "late" condition (Fig. 8B). However, no effect involving condition was close to significance. The IOI × PS interaction fell just short of significance, $F(36,324) = 2.11$ $p = .057$.

3.2.2. Phase correction response (PCR)

Fig. 9A shows the mean slope of the PCR function (i.e., PCR as a function of RPS, not PS) as a function of IOI and condition (filled and open circles; the triangles will be discussed later). The mean PCR increased significantly with IOI, $F(4,36) = 9.86$, $p < .001$, with only the linear trend being significant, $F(1,9) = 23.67$, $p = .001$. The mean PCR was also larger in the "late" than in the "early" condition, $F(1,9) = 8.54$, $p = .017$, except at the fastest tempo, where the difference seemed to be reversed.

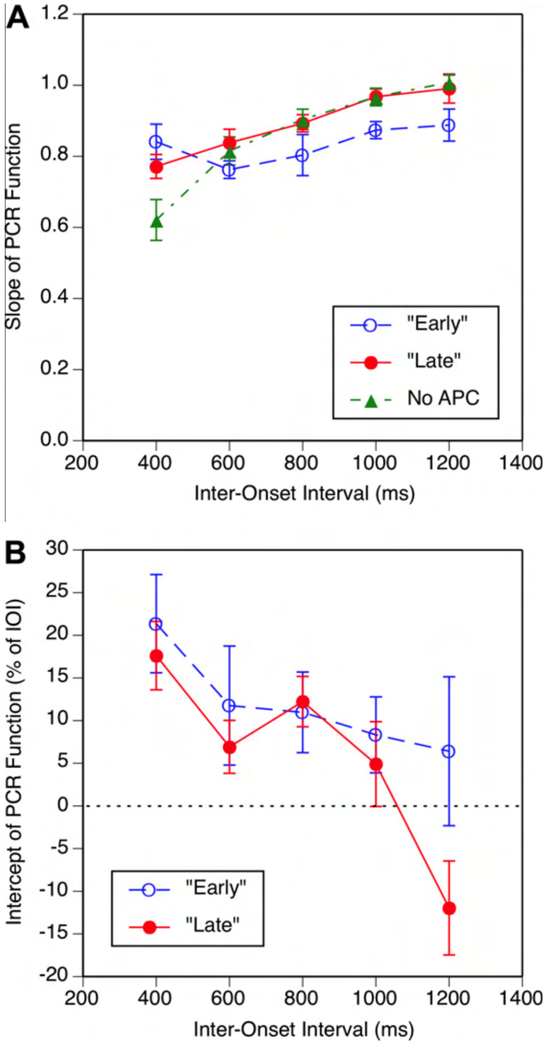

Fig. 9. Mean (A) slopes and (B) intercepts of PCR functions as a function of condition and IOI in Experiment 2. The "no APC" function in panel A is from Repp (2011b: Experiment 2). Error bars are ±1 standard error.

However, the Condition × IOI interaction did not reach significance, $F(4,36) = 2.52$, $p = .081$. While the mean PCR was quite large in all conditions, it did not exceed 1 at the slowest tempo.

Fig. 9B shows the mean intercept of the PCR function as a function of IOI and condition. Like the intercept of the APC function, it was positive at the faster tempi, here indicating more effective phase correction for positive than for negative RPSs, and decreased as IOI increased, $F(4,36) = 4.72$, $p = .012$. The main effect of condition and the interaction were not significant. These data suggest that positive RPSs were responded to more effectively than negative RPSs when the tempo was fast.

To confirm this suggestion, Fig. 10 plots the mean linear slopes of separate PCR functions for negative and positive RPSs as a function of condition and IOI (upright triangles and squares). Indeed, these slopes were shallower for negative than for positive RPSs at the fastest tempo, particularly in the "late" condition. At the other tempi, there was no difference in the "late" condition, whereas in the "early" condition there was, surprisingly, a similar asymmetry at the two slowest tempi, following an

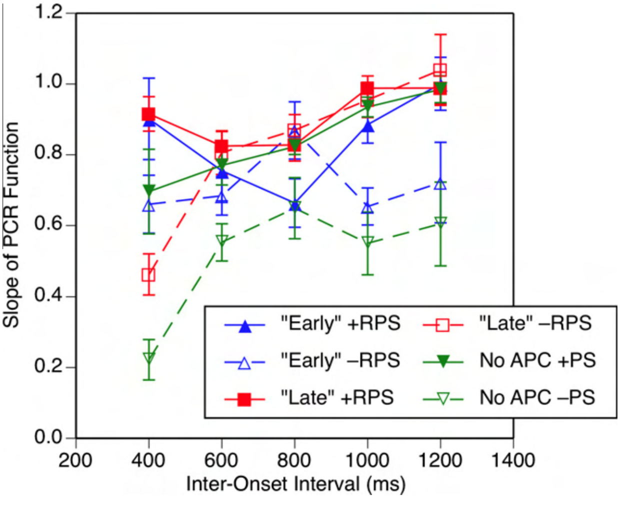

Fig. 10. Mean slopes of separate PCR functions for positive and negative phase shifts as a function of condition and IOI in Experiment 2. The "no APC" functions are from Repp (2011b: Experiment 2). Error bars are ±1 standard error.

opposite asymmetry at IOI = 800 ms. A 2 × 2 × 5 ANOVA confirmed significant main effects of IOI, $F(4,36) = 8.28$, $p = .001$, and of condition, $F(1,9) = 10.24$, $p = .011$. The main effect of direction fell just short of significance, $F(1,9) = 4.67$, $p = .059$, but the Direction × IOI interaction, $F(4,36) = 7.19$, $p = .006$, and the triple interaction, $F(4,36) = 3.75$, $p = .024$, were significant. Separate 2 × 5 ANOVAs on each condition showed the Direction × IOI interaction to be significant both in the "early" condition, $F(4,36) = 2.13$, $p = .033$, and in the "late" condition, $F(4,36) = 8.61$, $p < .001$. While the main effects were not significant in the "early" condition, in the "late" condition there was a highly reliable main effect of IOI, $F(4,36) = 17.32$, $p < .001$, even though the Condition × IOI interaction had not reached significance in the combined analysis of the two conditions. The main effect of direction was marginally significant in the "late" condition, $F(1,9) = 5.10$, $p = .050$.

A final analysis addressed whether the PCR to the RPS following APC was in any way different from the PCR to an unanticipated PS (i.e., without APC). Relevant data were available from Experiment 2 in Repp (2011b), which had used a standard PS paradigm with PS magnitudes ranging from −50 to 50%, the same five IOIs, and a similar group of musically trained participants (the same as in the present Experiment 1, but without coauthor GPM). Although three of the participants were the same as in the present experiment, the two groups were treated as independent in the following comparisons. The "no APC" slopes of the complete PCR functions are plotted as triangles in Fig. 9. Two mixed-model 2 (experiments) × 5 (IOIs) ANOVAs comparing either the "early" or the "late" condition mean PCRs (i.e., slopes of complete PCR functions) to the "no APC" PCR data did not reveal any significant overall differences in PCR magnitude between experiments, but the Experiment × IOI interaction was significant in each condition, $F(4,72) = 9.64$, $p < .001$, and $F(4,72) = 4.11$, $p = .015$, respectively. In the earlier study, the mean PCR increased from about 0.6 at the fastest tempo to about 1 at the slowest tempo according to a negatively accelerated function. At the slower tempi, it was thus similar to the present mean PCR in the "late" condition, but at faster tempi it was clearly smaller than the present PCRs in both conditions (see Fig. 8A).

By fitting separate regression lines to the PCR functions for negative and positive PSs, Repp (2011b) also found that the mean PCR to negative PSs was substantially smaller than the mean PCR to positive PSs at all IOIs. While the mean slope for positive PSs was similar to the slope of the whole PCR function, the slope for negative PSs was shallower, which also implies a steeper slope of the whole PCR function in the vicinity of zero (i.e., between PSs of −10% and 10%). This can be seen in Fig. 10 (inverted triangles). An ANOVA comparing the separate slopes for negative and positive RPSs in the present ''early'' condition to the ''no APC'' data here yielded a significant main effect of experiment, $F(1,18) = 5.63$, $p = .029$, indicating larger PCRs in the present experiment, and a marginally significant Experiment × IOI interaction, $F(4,72) = 3.02$, $p = .048$. The analogous ANOVA comparing the ''late'' condition with the ''no APC'' data yielded a clear difference between experiments, $F(1,18) = 18.09$, $p < .001$, again indicating larger PCRs in the present study. In addition, the Experiment × Direction interaction was significant, $F(1,18) = 8.09$, $p = .015$, because the difference between experiments was more pronounced for negative (R)PSs. Main effects of direction and IOI, and the Direction × IOI interaction were highly reliable in both ANOVAs.

3.3. Discussion

The results of Experiment 2 demonstrate, first of all, that musically trained participants can use analog visual cues to anticipate PSs of various magnitudes with reasonable accuracy. However, the data also reveal constraints on this APC ability. First, as in Experiment 1, APC was generally conservative, undershooting the actual magnitude of the PS. Even under the most favorable conditions, participants anticipated only about 80% of the PS, on average. Second, APC was clearly more difficult when the advance information was presented late and the tempo was fast. Third, it was more difficult to anticipate negative PSs than positive PSs when the tempo was relatively fast. These differences largely disappeared when the IOI duration reached 800 ms, suggesting that up to 800 ms may be needed to effectively implement a change in motor timing within an isochronous series of taps.

The reason for the conservatism of APC is not clear. It could be that participants generally underestimated the PS magnitude indicated by the visual slider, or they may have been resistant to shifting their taps by a large amount in either direction. It should be noted that participants did not shift their taps readily into anti-phase (±50%).

The asymmetry between negative and positive APC resembles that observed in the PCR to unanticipated PSs, where the response to negative PSs is likewise less effective than the response to positive PSs, especially at fast tempi (Repp, 2011b). When the tempo is fast, the tapping movement becomes more continuous and more resistant to a change in timing (Repp, 2005). At a fast tempo, advancing a tap is more difficult than delaying it because there is less time available after the preceding tap to change the planning of the movement of the next tap. Another parallel with the PCR was suggested by the data: Like the PCR, APC seemed to be somewhat less effective for large than for small PSs, as indicated by the mostly sigmoid APC functions. In addition, there seemed to be an even steeper slope between PSs of −10% and 10% of the IOI, a region not explored here for obvious reasons, as smaller magnitudes would have been difficult to perceive visually and execute motorically. This steeper central slope could also have been an artifact of the way in which the magnitude information was conveyed visually, or it may reflect a difficulty of making very small adjustments in timing, resulting in less conservative APC with small PSs.

The pattern of APC variability was initially surprising. Note that standard deviation was expressed as a percentage of IOI duration and thus was turned into a coefficient of variation (CV). One might have expected the CV to remain constant or increase with IOI duration, but in fact it decreased as IOI increased. This suggests that task difficulty (which increased as IOI decreased) was a more important determinant of variability than the absolute magnitude of APC. In addition, one might have expected the CV to increase with the absolute magnitude of APC. Or, if task difficulty determined variability, negative APC might have been expected to be more variable than positive APC. In fact, it was just the opposite, especially for large PSs. It seems that negative APC, while more difficult, was constrained by some limit of temporal adjustment that also constrained variability. By contrast, the large variability of positive APC may indeed reflect the magnitude of the adjustment made.

The mean PCR to RPSs showed some similarities with the mean PCR to unanticipated PSs, as was fully expected. In particular, it increased with IOI duration, and it was smaller for negative than for positive RPSs, at least when the tempo was fast. Interestingly, however, it tended to be larger than in the previous study with unpredictable PSs (Repp, 2011b). While this could simply be a difference between participants groups, it does suggest that preparation aids phase correction, in agreement with the results of Experiment 1.

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Given that APC was generally conservative (i.e., an undercorrection), APC and the PCR usually represented shifts of successive taps in the same direction. An enhanced PCR following APC therefore is consistent with the possibility that participants carried out some modest period correction in the course of APC that carried over to the next inter-tap interval. However, if all of APC had been due to period correction, and if the changed period had persisted, the mean PCR should have reflected substantial *overcorrection* of the RPS, which was not the case. Locally restricted period correction amounts to cognitively controlled phase correction. Therefore, the PCR results suggest that APC was due to phase correction, albeit under cognitive control, perhaps with a small admixture of period correction.

4. Summary and conclusions

The present sensorimotor synchronization study investigated musically trained participants' ability to anticipate phase shifts (PSs) of various magnitudes by shifting their coincident taps when they are given advance information about the PS. In Experiment 1, they were given only partial information about the PS's direction, position, or both, with PS magnitude remaining unpredictable. Participants showed anticipatory phase correction (APC) when they knew both direction and position of a PS, but the magnitude of APC corresponded only to that of the smaller of two possible PS magnitudes, indicating that APC was conservative. The phase correction response (PCR) to the residual PS (RPS) was enhanced compared to the PCR to an unpredictable PS, and information only about PS direction also enhanced the PCR somewhat, suggesting that preparation aids reactive phase correction.

In Experiment 2, we provided complete advance information about PS position, direction, and magnitude using a visual analog display. The information was provided either "early" or "late", and there were five different sequence tempi. APC was again found to be conservative, not exceeding 80% of the PS on average. In the "late" condition, APC depended strongly on tempo, becoming increasingly difficult and hence smaller as the tempo increased, particularly when the PS was negative. Clearly, it was more difficult to advance a tap than to delay it when the tempo was fast. An obvious reason might be that there was much less time between the visual cue and the motor response in the case of an advance than in the case of a delay. However, a similar asymmetry was seen when the visual cue was presented "early", which suggests that the main constraint came from the tapping tempo (the inter-tap interval), not from the time between cue and response.

Tempo also constrained the PCR to the RPS, though only at the fastest tempo (IOI = 400 ms) and only when the RPS was negative. Participants corrected well for positive RPSs even at the fastest tempo, actually somewhat better than at an intermediate tempo. Interestingly, the mean PCR to the RPS tended to be larger than the mean PCR to unpredictable PSs (Repp, 2011b), which may have been due to partial engagement of a period correction mechanism in APC. However, as in the experiment with unpredictable PSs, which used the same perturbation magnitudes, there was no overcorrection, not even at the slowest tempo.

On the whole, the results of this study suggest that, while reactive phase correction is typically automatic and subconscious (Repp, 2000; Thaut et al., 1998), phase adjustments can also be controlled consciously and implemented on cue in an anticipatory fashion, at least by musicians. Non-musicians might be less accurate in this task, but there is no reason why the skill should be specific to musicians. Musicians probably benefit the most from it, however, because anticipatory adjustments are often required in musical ensemble performance. While the way in which advance information was provided in this study is not typical of musical contexts, the temporal flexibility required by the task was probably comparable to that required in music performance.

Acknowledgments

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