

Toward a Psychophysics of Agency: Detecting Gain and Loss of Control Over Auditory Action Effects

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Theories of *agency*—the feeling of being in control of one's actions and their effects—emphasize either perceptual or cognitive aspects. This study addresses both aspects simultaneously in a finger-tapping paradigm. The tasks required participants to detect when synchronization of their taps with computer-controlled tones changed to self-controlled production of tones, or the reverse. For comparison, the tone sequences recorded in these active tapping conditions were also presented in passive listening conditions, in which participants had to detect the transition from computer to human control, or vice versa. Signal detection theory was applied to separate sensitivity from bias. Sensorimotor cues to agency were found to increase sensitivity in the active conditions compared with the passive conditions, which provided only perceptual cues. Analysis of bias revealed a tendency to attribute action effects to self-control. Thus, judgments of agency rely on veridical sensorimotor cues but can also be subject to cognitive bias.

Keywords: agency, sensorimotor synchronization, finger tapping, feeling in control, action effects

The impression that people willfully control their own actions and that others willfully control their actions is a crucial building block of private and public lives. This is the feeling of *agency*. Surprisingly little research has been conducted on this topic until very recently. Possible reasons include (a) scientists' perception that agency is not a topic of scientific study (cf. Frith, 1992; Wegner, 2002), (b) the neglect of action in cognitive psychology (cf. Prinz & Hommel, 2002; Rosenbaum, 2005), and (c) the challenge of finding viable experimental designs for study of the cognitive and neural mechanisms underlying the sense of agency (cf. Knoblich & Sebanz, 2005). In this article, we introduce a new approach that makes it possible for researchers to examine the joint influence of perceptual cues, sensorimotor cues, and cognitive bias on agency judgments.

Theories of Agency

Researchers in the fields of social psychology, cognitive neuroscience, and cognitive neuropsychiatry have recently started to consolidate their efforts to obtain a better understanding of agency

(cf. Frith, Blakemore, & Wolpert, 2000; Jeannerod, 2003; Kircher & David, 2003; Knoblich, Elsner, Aschersleben, & Metzinger, 2003; Wegner, 2002). Wegner (2002) provided a theoretical framework according to which one's sense of causing and controlling one's actions arises from inferences one draws after having carried out the actions. A person infers that he or she has caused an action if it was preceded by a thought (priority) that is consistent with the consequences of the action (consistency) and if no alternative cause of the consequences is evident (exclusivity). In ambiguous situations, individuals can experience illusions of control: feeling themselves controlling events that they did not actually cause. Wegner and colleagues (Wegner, Fuller, & Sparrow, 2003; Wegner, Sparrow, & Winerman, 2004; Wegner & Wheatley, 1999) have provided empirical evidence that this sense of agency can be mistaken. For instance, in Wegner et al. (2004), participants felt that they were controlling another person's body movements after hearing an instruction that predicted the other person's movement.

The theory of internal models (Davidson & Wolpert, 2003; Frith, Blakemore, & Wolpert, 2000; Wolpert & Kawato, 1998) suggests that sensorimotor signals provide important agency cues. This theory postulates two functionally different components in motor control: *Inverse models* specify movements that implement goal-directed actions, and *forward models* compute predictions about the sensory consequences of movements. Most relevant for the present purpose is the proposal that comparisons of the predicted and the actual sensory consequences of actions might yield cues to agency (Frith et al., 2000). Discrepancies might alert one to the presence of an external influence and, thus, reduce the strength of felt agency.

The theory of internal models has received wide empirical support. Discrepancies between the predicted and actual sensory consequences of actions affect tactile sensations (Blakemore,

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2003; Blakemore, Wolpert, & Frith, 1998, 2000), visual perception (Leube et al., 2003), and the perceived time of an action and its consequences (Haggard, Clark, & Kalogeras, 2002; Haggard & Clark, 2003; Haggard, 2005). There is also evidence that such discrepancies might influence explicit judgments of agency. In a seminal study, Daprati et al. (1997) showed that patients with schizophrenia find it more difficult than do healthy controls to distinguish their own hand movements from somebody else's hand movements in a visual display. Similar results have been obtained in patients suffering from parietal lesions (Sirigu, Daprati, Pradat-Diehl, Franck, & Jeannerod, 1999; Sirigu et al., 2004). These results suggest that the detection of temporal and spatial mismatches between the predicted and actual sensory consequences of actions plays a crucial role in determining agency. Subsequent studies in healthy adults and different patient groups have further confirmed the role of temporal and spatial mismatches in agency detection (Farrer et al., 2003, 2004; Fournieret, Franck, Slachevsky, & Jeannerod, 2001; Franck et al., 2001; Knoblich & Kircher, 2004; Knoblich, Stottmeister, & Kircher, 2004; Sato & Yasuda, 2005; van den Bos & Jeannerod, 2002).

A third theory of agency (Jeannerod, 1999, 2003) starts with the assumption of common coding for perception and action (Hommel, Müssele, Aschersleben, & Prinz, 2001; Jeannerod, 1997; Prinz, 1997). According to this theory, actions are represented in terms of their sensory consequences. Therefore, perception of others' actions results in the activation of the same representations that are used in action control. Mirror neurons in the macaque premotor cortex implement this principle on a single-cell level (Rizzolatti & Craighero, 2004). Imaging studies have provided evidence that humans possess a similar system (Iacoboni et al., 1999). Together, these findings suggest a wide overlap in cortical activation between self-produced and other-produced actions (Blakemore & Decety, 2001).

However, common coding of perception and action creates a problem for attributing actions to their proper agent. Jeannerod and colleagues' theory of agency (Georgieff & Jeannerod, 1998; Jeannerod, 1999, 2003; Vignemont & Fournieret, 2004; see also Ruby & Decety, 2001) is an attempt to solve this problem. They proposed a *who-system* that serves to attribute actions to self and other. It is assumed that this system keeps track of which motor representations are activated from within, as a consequence of one's own intentions, and which are not. This assumption provides an alternative explanation for some of the results described earlier and has received further support in a series of recent studies (Tsakiris, Haggard, Franck, Mainy, & Sirigu, 2005; Tsakiris & Haggard, 2005) that suggest that *effluent* signals related to implementing an intention provide important cues to agency.

Synchronization and Pseudo-Synchronization

Agency research is in need of further experimental paradigms that assess the various aspects of the feeling of agency as precisely as possible. So far, the focus of research has been on simple spatial transformations or constant temporal delays in action feedback. In the present study, we developed a new task that was inspired by research on sensorimotor synchronization. This task allowed us to examine some temporal cues to agency that have not been studied so far. Moreover, the relative importance of purely perceptual cues

and sensorimotor cues to agency could be determined, and cognitive biases could be identified.

Sensorimotor synchronization is studied most often by requiring participants to tap their finger in time with a machine-controlled sequence of auditory stimuli (for a review, see Repp, 2005). Studies of motor timing often focus, instead, on self-paced tapping that is preceded by synchronization with an auditory pacing sequence, to induce participants to tap at a particular rate. This is known as the *synchronization-continuation* paradigm (Stevens, 1886; Wing & Kristofferson, 1973a, 1973b). The transition from synchronization to continuation tapping is always clear because the pacing tones cease to sound.

Fraisse and Voillaume (1971) introduced a version of the synchronization-continuation task in which each continuation tap triggers a tone that sounds just like the tones of the preceding pacing sequence (*pseudo-synchronization*). Thus, the transition from synchronization to continuation tapping is obscured, and participants may not realize immediately that it has occurred. They may persist in the belief that they are synchronizing with externally controlled tones, even though the tones are occurring as a consequence of their own actions. Thus, the task creates a situation that is ambiguous with respect to agency.

Although Fraisse and Voillaume (1971) were aware of this ambiguity, their aim was not to investigate agency but to deprive participants of the information provided by asynchronies between taps and tones during synchronization. Asynchronies are typically negative in musically untrained participants: The taps precede the pacing tones by a few tens of milliseconds (Aschersleben, 2002, 2003). Fraisse and Voillaume instructed participants in one group to stay in synchrony with the tones and did not inform them about the transition. Another group of participants was told about the transition, and a visual cue indicated its precise time. Participants in the uninformed group dramatically accelerated their tapping after the transition. Basically, they believed that the pacing sequence had accelerated (although it was in fact their own tapping that had speeded up) and tried to stay in synchrony with it by speeding up further. Participants in the informed group also tapped faster after the transition, but the tempo change was smaller and not progressive, presumably because their intention was to keep tapping at the same tempo. In both groups, the acceleration can be understood as a tendency to restore the negative asynchrony (which corresponds to subjective synchrony) after the transition. This tendency can be eliminated by introducing delays between the taps and the tones during pseudo-synchronization (Flach, 2005; Vos, Helsen, & van Kruysbergen, 1992).

Flach (2005) further investigated the possible role of the feeling of agency in this task. In three experiments, he varied participants' knowledge about the transition (no knowledge, accurate information, and incorrect information, respectively) but found the same small acceleration of tapping after the transition. He did not observe a dramatic acceleration in uninformed participants, presumably because he used only a single sequence tempo and instructed participants to keep the tempo. Flach concluded that the acceleration in tapping speed is automatic and independent of participants' realization that they are controlling the tones. He wondered how quickly uninformed participants might detect the transition but did not collect any explicit agency judgments.

The Present Study

In the present study, we collected explicit judgments of agency in the task introduced by Fraitse and Voillaume (1971). Specifically, we investigated the feeling of being in control of tones that constitute potential auditory action consequences (cf. Sato & Yasuda, 2005). The feeling of agency for the tapping movement itself was assumed to be strong at all times on the basis of constantly available sensory (proprioceptive, tactile, and visual) information. During synchronization, the tones were externally controlled by a computer (*E-control*); after the transition to pseudo-synchronization, they were self-controlled (*S-control*)—that is, they occurred as consequences of the taps. Participants knew that an E–S transition in control mode was likely to occur, but they did not know when. Their task was to report when they discovered that they were in control of the tones.

The E–S condition was compared with an S–E condition, used here for the first time (but see Semjen, Vorberg, & Schulze, 1998, for a somewhat related design). In this condition, participants first controlled the tones themselves, and then at some point external (i.e., computer) control took over, so that participants found themselves synchronizing with the tones. Accordingly, participants were asked to report when they discovered that they had lost control over the tones.

In addition to these two *active* tapping conditions, we included two *passive* listening conditions in which participants heard the exact tone sequences recorded in the active conditions. Again, participants were asked to detect and report the occurrence of an E–S or S–E transition, but now the transition referred to their past action. In other words, they had to detect the change from a computer-controlled to a human-controlled sequence of tones, or vice versa. Because we used a detection paradigm in which responses could be hits or false alarms, basic signal detection theory could be applied to derive separate indices of sensitivity and bias for each of the four conditions.

Figure 1 reviews the agency cues available in our tasks. *Perceptual cues* (mean and variability of tone interonset intervals [IOIs]) were available in both active and passive tasks, but *sensorimotor cues* (mean and variability of asynchronies between tones

and taps) were specific to the active conditions. Thus, we predicted that to the extent that sensorimotor cues inform agency judgments, sensitivity to transitions should be greater in the active than in the passive conditions.

Predictions were more complicated with regard to possible differences in sensitivity to E–S and S–E transitions. Consider first the passive conditions. The main perceptual cue to an E–S transition is the sudden presence of temporal variability in the tone sequence, whereas the main perceptual cue to an S–E transition is the sudden absence of such variability. We predicted that the presence of variability would be easier to detect than its absence, because temporal variability cannot occur in a regular sequence, whereas temporal regularity can occur locally by chance in a variable sequence. Accordingly, we expected that sensitivity to transitions would be greater in the passive E–S condition than in the passive S–E condition.

Now consider the active conditions. The main sensorimotor cue to an E–S transition is the sudden absence of asynchronies, whereas the main cue to an S–E transition is the sudden presence of (variable) asynchronies. Again, we expected the presence of asynchronies to be easier to detect than their absence, because near-zero asynchronies can occur by chance during synchronization, whereas asynchronies can never occur during pseudo-synchronization. This asymmetry, however, counteracts the asymmetry in the perception of the simultaneously available perceptual cues described in the preceding paragraph (see also Figure 1). Therefore, we predicted that there would be less difference in sensitivity between the active E–S and S–E conditions than between the passive ones.

We also expected there to be differences in cognitive bias among the conditions. In particular, we thought that participants might have a general cognitive bias toward feeling in control in the active conditions (cf. Wegner, 2002). If so, false alarms during synchronization (E-control), which reflect attribution to S-control, should be more frequent than false alarms during pseudo-synchronization (S-control), which reflect attribution to E-control. In the passive conditions, that difference should be smaller or absent.

Method

Participants

Because this was our first exploration of a new paradigm for the assessment of agency, we found it convenient to use a readily available group of highly motivated, musically trained participants who could be relied on to carry out the difficult tasks conscientiously and with maximum precision. The participants were 7 paid volunteers, ages 19–25 years (6 women, 1 man), and 1 author (B.H.R.; age 60).¹ All were regular participants in tapping and synchronization experiments in B.H.R.’s laboratory. Six played musical instruments at a professional level, and two were advanced amateurs with a minimum of 7 years of musical training.

Equipment and Materials

The experiment was controlled by programs written in MAX (Version 4.0.9) and running on an iMac G4 computer. The tones were generated on

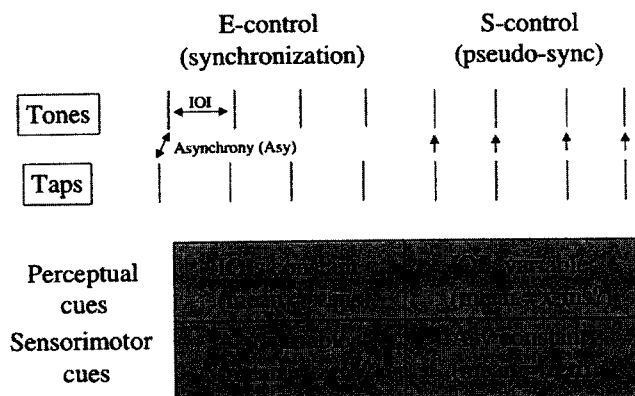


Figure 1. Schematic illustration of agency cues in the present tasks. E-control indicates external control by a computer; S-control indicates self-control. Question marks indicate possible but not essential cues. IOI = interonset interval.

¹ Although B.H.R. had had some prior experience with the tasks during preparation of the experiment and was much older than the other participants, his performance was not notably different.

a Roland (Nakagawa, Japan) RD-250s digital piano that was connected with the computer via a MOTU (Cambridge, MA) Fastlane-USB MIDI translator. The piano tones had a high pitch (E₇, MIDI pitch 100, 2637 Hz), sharp onsets, and no specified offset; their amplitude decayed exponentially within about 100 ms. Their peak intensity (MIDI key velocity) was constant.

E-S sequences consisted of 30 tones. S-E sequences started with 3 additional computer-controlled tones that served to induce the tempo of self-paced tapping and were followed by 30 tones. There were four nominal sequence tempi, corresponding to tone IOIs of 400, 500, 600, and 700 ms. E-S sequences started out at one of these tempi under E-control and then changed to S-control after the 8th, 12th, 16th, or 20th tone or not at all (catch trials). S-E sequences likewise started out at one of the four tempi under E-control (induction tones), continued with S-control, and changed to E-control after the 8th, 12th, 16th, or 20th tone (not counting the induction tones) or not at all.² To avoid an abrupt tempo discontinuity at the S-E transition, we had the computer adopt the final intertap interval before the transition as the constant IOI between tones after the transition. Four tempi and five transition positions (including no transition) resulted in 20 sequences that were presented in eight different randomizations (blocks) in each condition. In the active conditions, there was an extra practice block of 20 sequences at the beginning of the session.

Procedure

Participants came for four sessions that were usually 1 week apart and lasted 75–90 min. The active conditions made up the first two sessions, in one order for half the participants and in the other order for the other half, and the passive conditions followed in the same order, making up the last two sessions. In the passive conditions, the tone sequences recorded (as IOI sequences) during each participant's active conditions were replayed.³

Participants sat in front of the computer monitor, on which an incremental counter was displayed in a large font. The counter kept track of the number of tones that had occurred in a sequence. Participants started a trial by pressing the space bar, and then they closed their eyes. When they thought they had detected a transition, they opened their eyes briefly, glimpsed the number displayed on the screen, and closed their eyes again. At the end of the trial, they entered the remembered number in a dialog box. This procedure interfered minimally with tapping in the active conditions and was used also in the passive conditions for the sake of consistency. If no transition was detected, the response 30 was to be given at the end of the trial. If anything unusual happened during a trial (e.g., missed taps, gross irregularities of timing, lapse of attention), a participant could disqualify the trial by not entering any number.

The nature of the transition to listen for was explained carefully at the beginning of each session. Participants were told that the transition could occur anywhere in the sequence or not at all. Two points were stressed especially: First, participants were not permitted to revise any response on the basis of later counterevidence; whatever number was seen first on the screen was to be the response, even if it turned out to be a false alarm. Second, participants were urged to tap as accurately as possible in the active conditions, even though they thereby made the detection task hard for themselves.

Participants listened to the tones over Sennheiser (Old Lyme, CT) HD540 II headphones at a comfortable loudness level. In the active conditions, they tapped with their preferred hand (the right hand for all but 1) on a Roland SPD-6 percussion pad held on their lap. In the passive conditions, participants were instructed to sit still and listen during Blocks 2, 4, 6, and 8 and to tap along in synchrony with the tone sequences in Blocks 1, 3, 5, and 7. The purpose of this additional manipulation was to test whether the sensorimotor cues generated by the taps would provide any information helpful to the perceptual judgments. Tapping always started with the 3rd tone heard in a sequence. The impact of the finger on the rubber pad was audible as a thud, in proportion to the tapping force. The times of occurrence of the taps were recorded via MIDI. There were short

breaks between blocks during which the data were saved and a file representing the next block was read into the computer program.

Results

A total of 174 trials (3.4%) were lost to analysis. Of these, 97 (1.9%) were skipped or not recorded because of technical failure or human error, and 77 (1.5%) were not given any response (i.e., were disqualified) by the participants.

Slope Analysis

As a preliminary pass through the data, we analyzed the results for trials containing transitions using linear regression, on the basis of the reasoning that participants' responses (indicating the position at which they thought the transition occurred) should increase linearly with the actual position of the transition in the sequence. The method is illustrated in Figure 2 with arbitrarily chosen data from 1 participant in one particular condition at one particular sequence tempo. Eight responses are shown for each of the four transition points (8, 12, 16, 20), one response from each block of trials. The solid line is the identity line. Any data point on or below that line is a false alarm response, given before the transition actually had occurred. Any data point above the line is a hit, unless it falls on the upper margin of the graph (30), in which case it is a miss. The dashed line is a regression line fitted to all data points. Good performance would yield a slope close to 1, regardless of the mean delay needed to detect a transition. Poor performance would yield a slope close to 0.

On the basis of the slope values obtained from all such data sets, we decided to exclude one participant's data from further analysis. Table 1 shows individual participants' mean slopes in the four conditions. It can be seen that participant P7 basically performed at chance level (mean slope close to 0) in both active conditions as well as in the passive S-E condition. The poor performance in the active conditions was largely a result of a huge self-attribution bias: P7 very quickly felt in control during synchronization and hardly ever felt loss of control during pseudo-synchronization. We were surprised to see such results from a professional musician with excellent rhythmic skills; they suggest a possible impairment of the sense of agency.

The main results of the slope analysis, with P7 excluded, are shown in Figure 3. The slopes were submitted to repeated mea-

² Due to an unnoticed programming error, S-control of tones in the S-E condition began 3 tones later than intended: It was supposed to begin immediately following the 3 uncounted precursor tones (i.e., with Tone 1) but actually began with Tone 4. Consequently, because the S-E transition occurred after Tones 8, 12, 16, or 20, it occurred after only 5, 9, 13, or 17 S-controlled tones. It is unlikely that this had any effect on the results; at most, it may have made detection of an early transition slightly more difficult. Moreover, because tapping in the E-S condition began on Tone 3, the E-S transition occurred after only 6, 10, 14, or 18 taps with E-controlled tones. Thus, the E-S and S-E conditions were actually more similar in terms of the number of taps in one control mode before the other control mode took over than they would have been without the programming error.

³ Replay of S-E sequences included the 3 precursor tones. For technical reasons, the program added a constant 2 ms to all IOIs replayed, which resulted in a slight slowing of tempo (0.3%–0.5%).

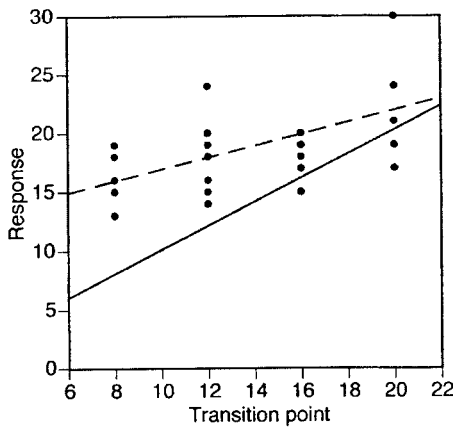


Figure 2. Illustration of slope analysis (see text for details).

tures analysis of variance (ANOVA) with condition (active vs. passive), transition type (E-S vs. S-E), and IOI (400, 500, 600, or 700 ms) as variables. Slopes were significantly steeper (indicating better detection performance) in the active than in the passive conditions, $F(1, 6) = 50.3, p < .0001$, and they were also steeper for E-S than for S-E transitions, $F(1, 6) = 13.5, p < .01$. The Condition \times Transition Type interaction was not significant. Moreover, the main effect of IOI and all interactions involving IOI were nonsignificant.⁴ This means that participants' responses depended on the serial occurrence of sequence events, not on sequence tempo or elapsed time. Because of this result, we combined the data from the four tempo conditions in all subsequent analyses, which increased the number of data points for the calculation of d' and bias coefficients and simplified presentation of the results.

A separate ANOVA assessed the effect of tapping along with the sequences in the passive conditions (i.e., odd vs. even blocks). Contrary to expectations, tapping did not improve detection performance but seemed to interfere with it slightly; the effect was not significant. Therefore, we combined the data from odd and even blocks in the passive conditions in all subsequent analyses.

Table 1
Mean Slopes of Individual Participants in the Four Conditions

Participant	Condition			
	E-S active	S-E active	E-S passive	S-E passive
P1	0.54	0.28	0.45	0.08
P2 ^a	0.92	0.65	0.48	0.17
P3	0.56	0.47	0.41	0.14
P4	0.88	0.86	0.49	0.59
P5	0.71	0.53	0.44	0.22
P6	0.79	0.80	0.56	0.38
P7	0.03	0.07	0.44	-0.11
P8	0.64	0.40	0.37	0.33

Note. E-S denotes the transition from E-control (tones externally controlled by a computer) to S-control (tones self-controlled); S-E denotes the opposite transition. Active indicates an active listening condition, whereas passive indicates a passive listening condition.

^a B.H.R. (one of the authors).

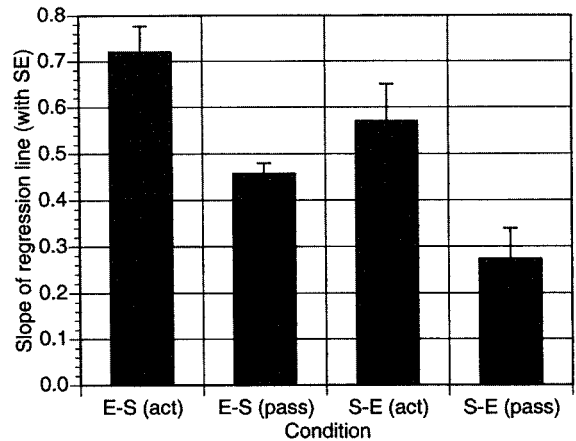


Figure 3. Mean slopes in the four experimental conditions. E-S = transition from E-control (tones externally controlled by a computer) to S-control (tones self-controlled); S-E = transition from S-control to E-control; act = active tapping condition; pass = passive listening condition. Error bars represent standard errors.

Proportions of Hits and False Alarms

Unlike a standard signal detection task, which yields only a single proportion of hits and a single proportion of false alarms, the present tasks yielded cumulative proportions of hits and false alarms as a function of sequence position. We obtained these proportions by extending the observation interval gradually from Position 1 to Position n ($n = 2-29$ in steps of 1), counting the responses given during the observation interval in all trials with the same transition point (8, 12, 16, 20, or none) and dividing that number by the total number of responses for those trials. The cumulative response proportions represent false alarms up to the transition point and hits afterwards. In catch trials, they represent false alarms only. We subsequently averaged the false alarm proportions across trials with different transition points, so there was only a single cumulative function of false alarm proportions in each condition, derived from both transition trials and catch trials.

The resulting mean cumulative hit and false alarm proportions for the four main conditions are shown in Figure 4. In each condition, there are four hit functions, each starting after a different transition point, and one false alarm function. The hit proportions generally exceed the false alarm proportions (which means that detection occurred), and all functions increase with sequence position.⁵ The hit functions for the four transition points are roughly parallel and tend to reach a common asymptote. The complement of the terminal hit rate is the proportion of misses. The complement of the terminal false alarm rate is the proportion of correct rejections.

⁴ Similar results were obtained in an ANOVA on the R^2 values of the regression line fits (the steeper the slope, the better the fit).

⁵ The nonmonotonicities in the false alarm functions at Position 20 in three of the conditions reflect the fact that for unknown reasons, false alarm responses tended to be somewhat more frequent in transition trials than in catch trials.

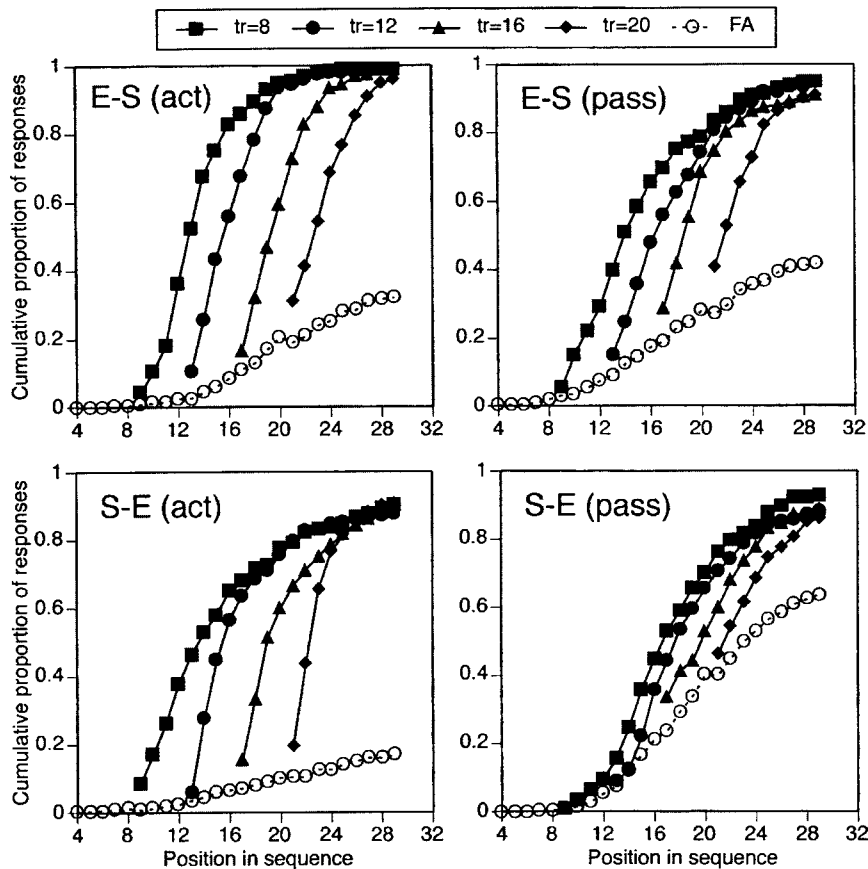


Figure 4. Cumulative hit and false alarm (FA) proportions in the four experimental conditions. tr = transition point; E-S = transition from E-control (tones externally controlled by a computer) to S-control (tones self-controlled); S-E = transition from S-control to E-control; act = active tapping condition; pass = passive listening condition.

Analysis of Sensitivity (d')

By computing the difference of the z -transforms of the hit and false alarm proportions in each sequence position, we obtained d' as a function of sequence position after each transition point from the individual participant data. To accommodate occasional hit or false alarm rates of 0 or 1, we added or subtracted the equivalent of half a response in those cases. Because several participants had extremely low false alarm rates in the active S-E condition, the d' results showed a somewhat different pattern from that of the initial slope analysis.

The d' functions are shown in Figure 5. Like the cumulative hit proportions, they are roughly parallel and tend to reach common asymptotes. This suggests that they are primarily a function of the serial distance (i.e., number of sequence events) from the transition point. Therefore, the d' functions were averaged across transition point conditions and expressed as a function of serial distance from the transition. These mean d' functions are shown in a single graph in Figure 6, which makes it easier to compare the four conditions. Note that there are increasingly fewer data points contributing to these mean d' functions as distance from the transition point increases; The rightmost data points derive exclusively from the trials with the earliest transition point (i.e., 8), and some minor

discontinuities in the functions are due to the successive dropout of transition conditions. Because of this data attrition, and because the d' values seem to reach a shallower slope or asymptote at approximately 9 events after a transition point, the d' values at that distance (to which all transition conditions still contributed) were selected for statistical analysis.⁶

A 2×2 repeated measures ANOVA on the d' values showed that sensitivity was significantly higher in the active than in the passive conditions, $F(1, 6) = 25.0, p < .002$, but the main effect of transition type (E-S vs. S-E) fell just short of significance, $F(1, 6) = 5.5, p < .06$. Instead, the Condition \times Transition Type interaction was significant, $F(1, 6) = 16.8, p < .006$. As can be seen in Figure 6, the active conditions did not differ from each other at Distance 9 or beyond, whereas the passive conditions differed all the way, with sensitivity being much higher in the E-S than in the S-E condition.

⁶ There seemed to be no point in including distance as a variable in the ANOVA. Obviously, it would have yielded a significant main effect and significant interactions with the other variables, given the pattern of the data shown in Figure 6.

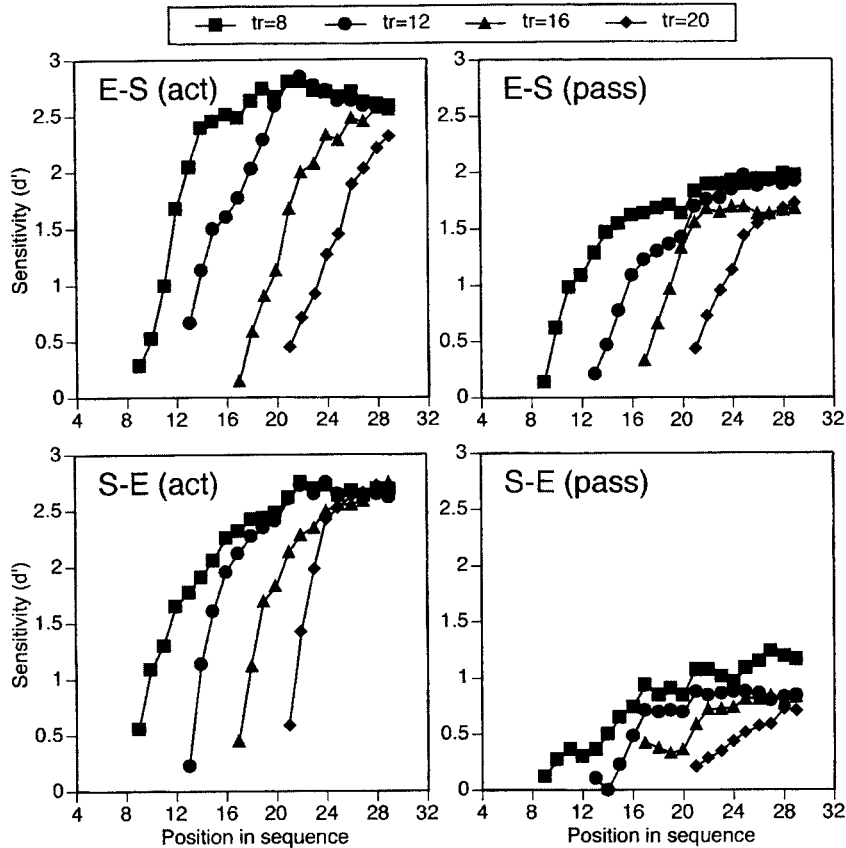


Figure 5. Values of d' as a function of sequence position in the four experimental conditions. tr = transition point; E-S = transition from E-control (tones externally controlled by a computer) to S-control (tones self-controlled); S-E = transition from S-control to E-control; act = active tapping condition; pass = passive listening condition.

Analysis of Bias

As our principal measure of bias, we used the z -transforms of the false alarm rates, $z(FA)$, shown in Figure 4. According to the assumptions of signal detection theory (Macmillan, 1993), this measure represents the distance of the response criterion from the mean of the hypothetical "noise" distribution in standard deviation units. We preferred this measure to other possible bias indices (c or β) because it is independent of hit rates and, hence, also of transition points. Figure 7 shows the mean bias coefficients from Position 11 onward. (Prior to this position, the coefficients were unreliable because of low false alarm rates.)

Unlike the d' functions, the bias functions did not reach an asymptote but continued to increase as a function of sequence position within the range studied. Therefore, we conducted a repeated measures ANOVA on the terminal bias values (Position 29). It showed that there was significantly greater bias in the passive than in the active conditions, $F(1, 6) = 23.8, p < .003$. In addition, there was a significant Condition \times Transition Type interaction, $F(1, 6) = 7.4, p < .04$: Bias was greater in the active E-S than in the active S-E condition, but it was smaller in the passive E-S than in the passive S-E condition. The main effect of transition type was not significant. It should be noted that bias with E-S transitions represents S-attribution during E-control, whereas bias with S-E transitions represents E-attribution during S-control.

There were large individual differences. Table 2 shows the terminal bias indices for individual participants. Two participants (P2, P8) gave no false alarm responses at all in the active S-E condition, and there was a wide range of bias indices in all conditions. (Note that a value of 0 represents 50% false alarm responses.) Nevertheless, there was some consistency in the pattern of differences: All but one participant showed greater bias in the passive than in the active E-S condition; all showed greater bias in the passive than in the active S-E condition; all but one showed greater bias in the active E-S than in the active S-E condition; and all but two showed greater bias in the passive S-E than in the passive E-S condition.⁷

⁷ We also analyzed the data using c (the mean of the z -transformed hit and false alarm proportions) as an index of bias, which depends on hit proportions and, thus, on the transition point as well as on sequence position. Nevertheless, the bias functions for different transition points converged on nearly the same terminal value in each condition. In an ANOVA on the terminal values of c , only the main effect of condition reached significance, $F(1, 6) = 9.46, p < .03$. The results resembled those reported for our preferred index of bias (see Figure 7) in that they indicated a lower bias in the active S-E condition than in the other three conditions.

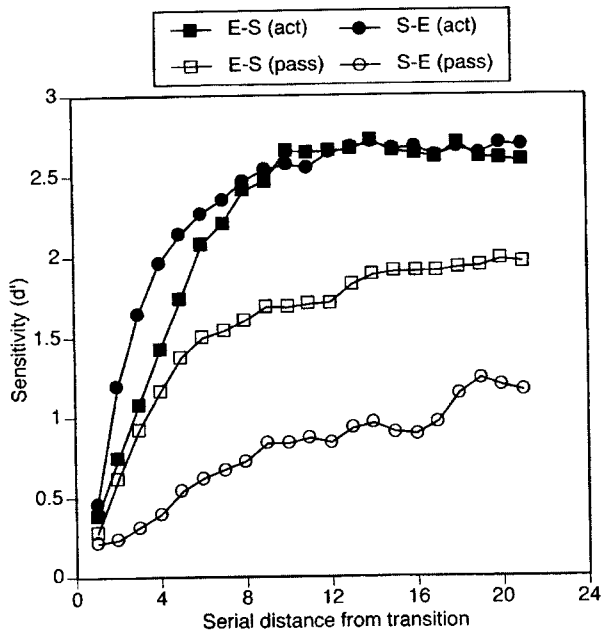


Figure 6. Mean values of d' as a function of distance from the transition in the four experimental conditions. E-S = transition from E-control (tones externally controlled by a computer) to S-control (tones self-controlled); S-E = transition from S-control to E-control; act = active tapping condition; pass = passive listening condition.

The Role of Local Agency Cues

Potential perceptual and sensorimotor agency cues in the present tasks are summarized in Figure 1. Undoubtedly, some or all of

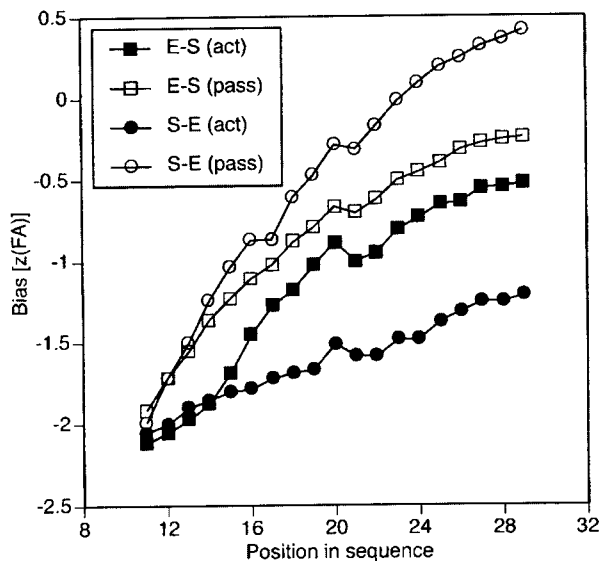


Figure 7. Mean bias indices (zero false alarm rates; $z[FA]$ s) as a function of sequence position in the four experimental conditions. E-S = transition from E-control (tones externally controlled by a computer) to S-control (tones self-controlled); S-E = transition from S-control to E-control; act = active tapping condition; pass = passive listening condition.

Table 2

Terminal Bias Indices ($z[FA]$ s) for Individual Participants in the Four Conditions

Participant	Condition			
	E-S active	S-E active	E-S passive	S-E passive
P1	-0.37	-1.09	0.33	1.22
P2 ^a	-1.01	-2.15 ^b	-0.16	0.67
P3	0.49	-0.40	0.00	1.15
P4	-0.37	-1.53	-0.20	-0.17
P5	-1.13	0.08	-0.29	0.25
P6	-1.15	-1.26	-0.20	-0.27
P8	-0.64	-2.15 ^b	-1.15	0.04

Note. E-S denotes the transition from E-control (tones externally controlled by a computer) to S-control (tones self-controlled); S-E denotes the opposite transition. Active indicates an active listening condition, whereas passive indicates a passive listening condition.

^a B.H.R. (one of the authors). ^b Minimal value of $z(FA)$, reflecting zero false alarm rate.

these cues contributed to participants' detection of a transition in control mode. One interesting question is whether the gradual increase in d' after a transition point represents a gradual accumulation of subliminal perceptual and sensorimotor information, accompanied by a gradually increasing or decreasing feeling of agency, or whether it reflects the increasing probability that a single, highly detectable cue will occur.

To address this issue, we aligned the asynchronies during E-control in the active S-E condition and the IOIs (equivalent to intertap intervals) during S-control in the active and passive E-S conditions to the sequence position at which a hit response was made. From these response-locked data, several measures were derived that may have served as agency cues. If hit responses were triggered by local detectable cues, then an increase in the mean magnitude of these measures should be observed in the positions immediately preceding hit responses.

Conversely, for false alarm responses, we asked whether they resulted from a continuously increasing expectation of a transition as the sequence progressed (an expectation whose strength is modulated by cognitive bias) or whether they were triggered by a momentary reduction in perceptual or sensorimotor information that served as a misleading cue. If the latter, then a decrease in the mean magnitude of variables having potential cue value should be observed preceding false alarm responses. The appropriate response-locked data were obtained from the asynchronies during E-control in the active E-S condition and from the IOIs (or intertap intervals) during S-control in the passive S-E condition. (There were not enough false alarms in the active S-E condition for reliable data to be obtained, and there was nothing to be measured in the passive E-S condition.)

Trials representing misses or correct rejections were not included in these analyses. Although Figures 8 and 9 show data for eight or seven serial positions preceding a response, ANOVAs were conducted on the last four positions only.

Figure 8 presents the results for asynchronies (sensorimotor cues). Figure 8A shows that the mean asynchrony did not change significantly before a hit or false alarm response, which means that responses were not triggered by consistent phase drift in the

negative or positive direction. Figure 8B shows the mean absolute asynchrony. Here, a clear increase can be seen in the two positions preceding a hit response, $F(3, 18) = 16.41, p < .001$.⁸ By contrast, the absolute asynchrony decreased slightly before a false alarm response, but the effect was not significant. A combined ANOVA showed a significant Condition \times Position interaction, $F(3, 18) = 11.45, p < .003$. Figure 8C shows a third measure, the mean absolute change in asynchrony. That measure, too, increased significantly before a hit response, $F(3, 18) = 19.75, p < .001$, and it also tended to decrease before a false alarm response, although that effect again did not reach significance, $F(3, 18) = 3.44, p < .07$. In a combined ANOVA, the Condition \times Position interaction was significant, $F(3, 18) = 15.27, p < .001$.

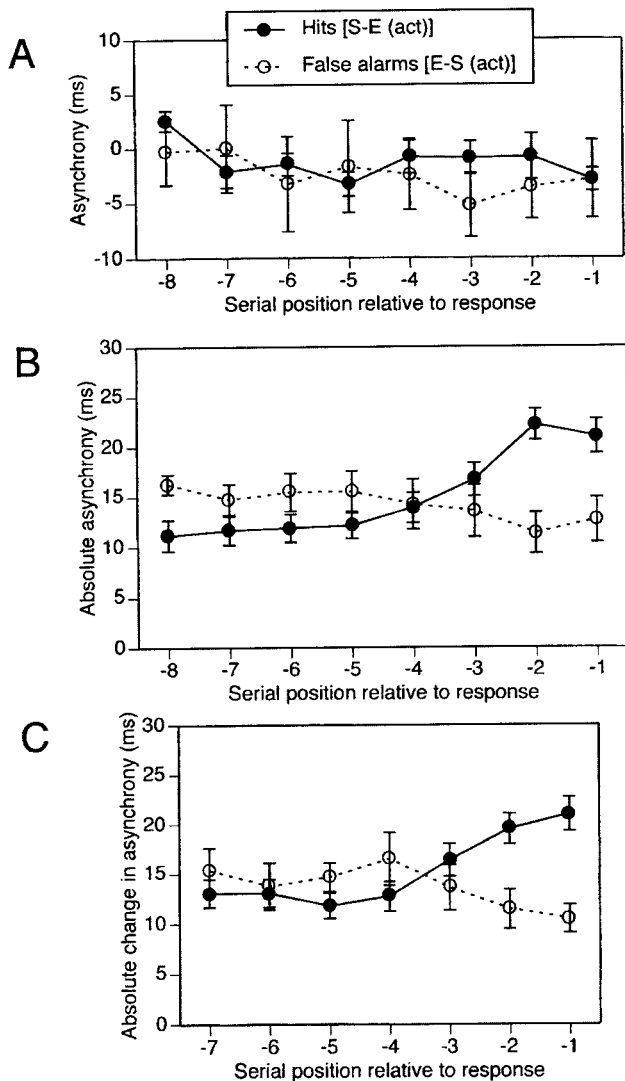


Figure 8. Mean asynchrony (A), mean absolute asynchrony (B), and mean absolute change in asynchrony (C) in the serial positions preceding a hit response in the active S-E condition or preceding a false alarm response in the active E-S condition. S-E = transition from S-control (tones self-controlled) to E-control (tones externally controlled by a computer); act = active tapping condition; pass = passive listening condition. Error bars represent standard errors.

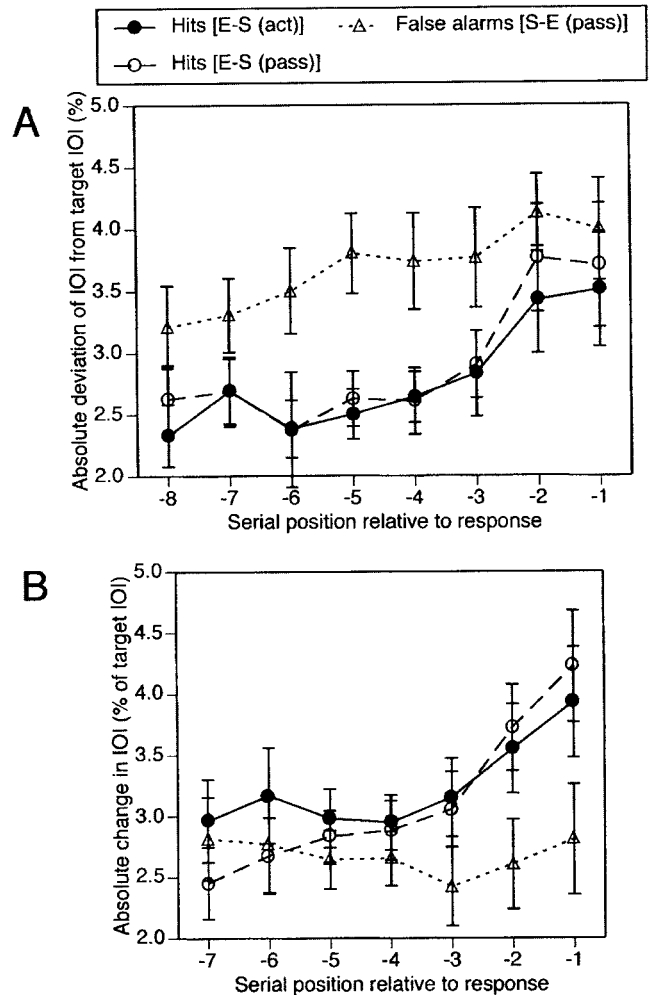


Figure 9. Mean deviation of current interonset interval (IOI) from the target IOI (A) and mean absolute difference between successive IOIs (B) in the serial positions preceding a hit response in the active and passive E-S conditions or preceding a false alarm response in the passive S-E condition. E-S = transition from E-control (tones externally controlled by a computer) to S-control (tones self-controlled); S-E = transition from S-control to E-control; act = active tapping condition; pass = passive listening condition. Error bars represent standard errors.

Figure 9 presents the results for tone IOIs (perceptual cues). Figure 9A shows the mean absolute deviation of the current IOI from the target IOI in percent, a measure of tempo drift during S-control (where the IOI is the same as the intertap interval). This measure clearly increased in the two positions preceding a hit response, $F(3, 18) = 8.26, p < .01$, and this was true in both the active and the passive E-S condition. (The Condition \times Position interaction was not significant in an ANOVA on the hit data.) There was no significant increase preceding a false alarm response. In a combined ANOVA on the hit and false alarm data from the passive conditions, however, the Condition \times Position interaction

⁸ The Greenhouse-Geisser correction was applied to the p levels of all F values having more than 1 degree of freedom in the numerator.

did not reach significance, $F(3, 18) = 2.92, p < .10$, which means that the increase was not reliably greater before a hit response than before a false alarm response. The main effect of condition was not significant either, although false alarm trials tended to show larger deviations from the target IOI than did hit trials. The likely reason for this is that on average, false alarms occurred later than hits during S-control, and deviations from the target tempo increased with sequence position.

Figure 9B shows the results for the mean absolute change between successive IOIs during S-control, expressed as a percentage of the target IOI (a kind of local coefficient of variation). Once again, a significant increase preceding a hit response was observed, $F(3, 18) = 9.60, p < .02$, and again it was similar in the active and passive E-S conditions. By contrast, there was no significant change preceding false alarms in the passive S-E condition, and in a combined ANOVA on the two passive conditions, the Condition \times Position interaction was significant, $F(3, 18) = 6.34, p < .02$, indicating that the increase before a hit response was significantly greater than that before a false alarm response. Thus, there is evidence that both sensorimotor cues and perceptual cues triggered hit responses, whereas false alarm responses were triggered by misleading cues—if at all—to a much lesser extent.

What about the cues followed by question marks in Figure 1? Changes in mean asynchrony and/or mean IOI are unlikely to be salient in the long run, because they require relatively long-term memory for their detection, but they could constitute cues immediately after a transition, as suggested by Flach's (2005) observations. One indication that these immediate cues were not particularly salient in the present study is the fact that d' started relatively low after a transition (see Figure 6). In each condition, the initial value of d' was generally not larger than the increase in d' from the first to the second posttransition position, which indicates that cues at a transition, though undoubtedly present, were no more salient than subsequent cues. One reason for this is that the mean asynchronies of the present, musically trained participants were close to 0 at all sequence rates (see also Figure 8A), both before E-S transitions and after S-E transitions. (They were, of course, exactly 0 during S-control.) Changes in IOI duration across an E-S transition were likewise rather small—less than 2% on average, which is near or below the detection threshold for tempo changes in musically trained listeners (Repp, 2001; Repp & Keller, 2004).⁹ Nevertheless, it is worth noting that the mean change in IOI across the E-S transition represented a small acceleration that occurred within one or two taps and did not continue further. This replicates Flach's (2005) findings.¹⁰

Discussion

The purpose of the present study was to examine the contributions of perceptual and sensorimotor cues and of cognitive bias to explicit judgments of agency with regard to auditory action effects, using a paradigm derived from the pseudo-synchronization task of Fraisse and Voillaume (1971). In active tapping conditions, participants had to detect a transition from external control (synchronization) over the tones to self-control (pseudo-synchronization), or the reverse, relying on sensorimotor and perceptual timing cues. In other words, participants had to judge whether they were synchronizing with the tones or whether they were controlling them.

In passive conditions, participants had to detect the transition from a computer-controlled, perfectly regular tone sequence to a human-controlled, temporally variable sequence, or the reverse, using only perceptual timing cues.

Even though the participants were musically trained and experienced in synchronization tasks, they found the tasks difficult and rarely detected the transitions immediately. This was in part due to their ability to tap with low variability (cf. Figure 9B). Detection performance (d') increased steeply after a transition until about 8–10 sequence events had occurred and then approached an asymptote. Each event in the sequence provided new timing information on which agency decisions could be based. Sequence tempo was not an important variable, because as interval duration increased, decreases in perceptual sensitivity for temporal variation (see, e.g., Friberg & Sundberg, 1995) were compensated for by increases in the actual variability produced (see, e.g., Madison, 2001; Peters, 1989) and to be detected (cf. Ivry & Hazeltine, 1995).

As predicted, transitions were significantly easier to detect in active than in passive conditions. Although all conditions shared perceptual agency cues, sensorimotor cues (asynchronies) were available only in the active conditions. Thus, the results suggest that both sensorimotor and perceptual cues were relied on in the active conditions. The difference in d' between active and passive conditions seems a reasonable estimate of participants' sensitivity to sensorimotor cues, because our analysis of response-locked perceptual cues indicated that perceptual cues were equally salient in active and passive conditions (see Figure 9).

In the passive listening conditions, E-S transitions were easier to detect than S-E transitions, as predicted. In an E-S transition, a completely regular computer-controlled tone sequence is followed by a variable human-controlled one, so detection of variability (as well as perhaps tempo drift) is required. By contrast, an S-E transition requires detection of regularity (as well as perhaps constancy of tempo) following a variable sequence. There are at least two reasons for the difference in sensitivity. First, exposure to a regular sequence sharpens the sensitivity to timing deviations, be it by means of a multiple-look, interval-based mechanism (Drake & Botte, 1993; Miller & McAuley, 2005) or by entrainment of an internal oscillator (Large & Jones, 1999; McAuley & Jones, 2003). By contrast, exposure to an irregular sequence has the opposite effect (Repp, 2002; Yee, Holleran & Jones, 1994), perhaps by increasing the variability of an internal timekeeper or oscillator, and thus it may give rise to perception of illusory variability where

⁹ IOI duration did not change across an S-E transition because the computer adopted the final pretransition IOI as the constant IOI after the transition. The pretransition IOI was generally shorter than the target IOI, especially for the longer target IOIs, reflecting a tendency to speed up during S-control.

¹⁰ Flach (2005) found a positive correlation between the mean asynchrony preceding an E-S transition and the change in IOI afterward, with the latter being about half the size of the former. It is interesting to note that that correlation (computed here across the 28 data points resulting from 7 participants and 4 target IOIs) was replicated as well, even though the range of mean asynchronies was much smaller ($r = .72, p < .001$). However, the slope of the regression line was considerably steeper than the approximately .5 found by Flach. It would lead too far afield to discuss the implications of these findings here.

there is none. Second, a regular sequence is by definition never irregular, so temporal irregularity is a sure indicator that an E–S transition has occurred. By contrast, an irregular sequence can by chance become nearly regular for a short time. Consequently, a longer stretch of regularity is needed to convince a listener that an S–E transition has occurred.

In the active conditions, there was no significant difference in sensitivity to E–S transitions and sensitivity to S–E transitions. (In fact, S–E transitions were initially somewhat easier to detect than E–S transitions [see Figure 6].) This predicted Condition \times Transition Type interaction was not apparent in the initial slope analysis because that analysis did not include catch trials; the interaction effect emerged only in the analysis of the sensitivity parameter d' . Clearly, it was caused by the low false alarm rates shown by several participants in the active S–E condition (see Table 2); these participants hardly ever reported having lost control of the tone sequence during S-control. Their low false alarm rates elevated the d' values in the active S–E condition. Their weak bias of attributing control to external forces (the computer) implies a strong bias toward self-attribution.

There were reasons for expecting little difference in d' values between the two active conditions: The presence of asynchronies following their absence may be easier to detect than the absence of asynchronies following their presence, for the same reason that presence of IOI variability following constant IOIs may be easier to detect than the reverse. Moreover, temporary near absence of asynchronies can happen during synchronization (E-control), whereas asynchronies can never arise during pseudo-synchronization (S-control). Because asynchronies were present when temporal variability was absent, and vice versa, the asymmetry in the detection of sensorimotor cues counteracted the asymmetry in the detection of perceptual cues that caused the difference in d' between the two passive conditions.

Our analysis of bias suggests that cognitive bias also affects agency judgments. For the present task, the z-transformed false alarm rate seemed to be the most appropriate bias measure. Other more commonly used measures like c or β seemed less appropriate because our paradigm differs from typical signal detection paradigms in that the cumulative hit rates *include* false alarms. Normally, there are independent *noise* and *signal* trials. In our paradigm, however, noise precedes a signal in the same trial (except for catch trials). A response given to the noise precludes a response to the signal. Therefore, a single cumulative response function needs to be considered—one in which false alarms become hits as soon as noise turns into signal.

We predicted that there might be a bias toward self-attribution, as has been observed in earlier studies of agency (e.g., Daprati et al., 1997). Such a tendency would be reflected in a higher false-alarm rate during E-control (synchronization) than during S-control (pseudo-synchronization) in the active conditions but not in the corresponding passive conditions. In other words, we expected that participants would be more likely to experience a computer-controlled pacing sequence as self-generated than to experience a sequence generated by one's own action as externally generated. The data for the active conditions were consistent with these predictions.

The passive conditions showed a difference in bias that was the opposite of that between the active conditions: Participants were more likely to say a human-controlled sequence was computer-

controlled than the reverse. Because cognitive self-attribution is not an issue in passive conditions—even when tapping along, participants knew very well that they were merely synchronizing with a previously recorded sequence—this difference can only be explained by a perceptual asymmetry. As we have already pointed out, a variable sequence can show stretches of very low variability, which may lead to the mistaken conclusion that a transition to E-control has occurred. However, our analysis of a response-locked index of local variability (see Figure 9B) did not provide support for the hypothesis that such patches of regularity in a variable sequence triggered false alarm responses. Nevertheless, it seems intuitively obvious that it is easier not to hear variability that is present than to hear variability when it is absent. Thus, there is likely to always be a greater bias to perceive sequences with small variability as regular than to perceive regular sequences as irregular.

Admittedly, a similar perceptual argument could be presented to explain the opposite difference in bias between the two active conditions. The difference could reflect an asymmetry in the detection of asynchronies, which are generally difficult to perceive during synchronization (see, e.g., Repp, 2000): Participants may have shown a tendency toward self-attribution not because of a cognitive bias but because they did not perceive asynchronies that were present, whereas they hardly ever perceived asynchronies when these were absent. The analysis of response-locked asynchronies provided only weak support for the hypothesis that patches of reduced asynchrony triggered false alarm responses during synchronization, but the general argument that it is easier to miss things present than to perceive things absent applies here too. To explain the reversed difference in bias relative to the passive conditions, however, it would have to be supposed that responses in the active conditions were dominated by sensorimotor cues, and this does not jibe with the d' results. Therefore, we believe that cognitive self-attribution bias made a substantial contribution beyond any perceptual asymmetries that may have been in effect.

The finding that there were fewer false alarms overall in the active than in the passive conditions is easily explained by the availability of sensorimotor cues in the active conditions, in addition to perceptual cues. The additional agency cues clearly reduced uncertainty about the mode of control, resulting in fewer incorrect responses.

Our analyses of data locked to hit responses aimed to determine whether hits were triggered by local salient cues or reflected the gradual accumulation of subliminal information—a slowly growing feeling of agency or of loss of agency. There was strong evidence that hit responses were indeed triggered by local salient cues, both sensorimotor and perceptual. We identified two sensorimotor cues during synchronization—absolute asynchrony and absolute change in asynchrony—that are of course not independent and are both sensitive to local irregularities in tap timing. We suspect that the absolute asynchrony was the perceptually more salient cue. The mean absolute asynchrony was about 20 ms preceding a hit response, which is similar to the detection threshold for temporal order in practiced listeners (Hirsh, 1959; Hirsh & Sherrick, 1961). We also identified two perceptual cues during S-control—the mean absolute deviation of the IOI from the target IOI and the mean absolute change in the IOI. These two cues are independent in that the first represents mainly tempo drift, whereas the second reflects local irregularities in tap timing. Here, the

second cue was probably more salient, because deviations from the target IOI may require long-term memory for their detection. The mean absolute change in IOI duration preceding a hit response was about 4%, which corresponds approximately to the detection threshold for interval differences (Drake & Botte, 1993; Friberg & Sundberg, 1995). Thus, it seems that detection of E-S transitions was partly based on local deviations of the tone sequences from temporal regularity.

This evidence for the importance of local salient cues does not rule out the possibility of simultaneous gradual accumulation of perceptual and sensorimotor information. In particular, gradual accumulation must have occurred if and when the absence of temporal deviation or variation provided an agency cue. In the passive S-E condition, the absence of temporal irregularities in the tone sequence was the only cue for E-control. In the active E-S condition, the absence of asynchronies was one of the cues for S-control. Such negative information is necessarily cumulative, and in our paradigm it amounts to detecting the perfect correlation between the timing of the taps and of the tones.

Another cumulative factor was the general expectation that a transition would occur in a trial, which increased with sequence position because the probability of a transition occurring increased with sequence position, from 0 to .8. That expectation, however, was the same across conditions and, thus, can only account for the cumulative increase in false alarms with sequence position, not for differences among conditions.

The present results were obtained with a special group of participants who were musically trained, cooperative, and experienced in synchronization tasks. The use of highly qualified participants in extended testing periods is consistent with general research practice in psychophysics. However, it can also be justified by noting that in studies of agency, participants are usually asked to carry out actions they are familiar with. A number of changes will have to be made to our paradigm to make it suitable for testing inexperienced participants, let alone patients who have an impaired sense of agency. Although the tasks are not easy, we do not expect them to be much more difficult for other participants, because they are *self-calibrating*: Participants with low perceptual sensitivity to timing variations are likely to produce large timing variability, and vice versa. The main challenges will be to obtain reliable data within a shorter time span (the present experiment took about 5 hr per participant) and to prevent participants from "cheating" by tapping intentionally with high variability.

The advantage of the present paradigm is that it allows us to separate the contributions of different perceptual and sensorimotor cues as well as of cognitive bias to judgments of agency. Furthermore, it allows us to quantify the feeling of agency in a cumulative manner, as a function of serial position in an event sequence. Both the gain and the loss of the feeling of agency can be addressed. The results show that agency is not derived from a single perceptual or sensorimotor cue or solely governed by cognitive biases. Rather, the evidence suggests that many factors can influence judgments of agency.

This insight has some important implications for current theorizing about agency. It seems that cognitive biases, such as the feeling of illusory control over external events (Wegner, 2002), occur especially in situations in which informative perceptual and sensorimotor cues are missing. Perceptual cues can be used to assess agency in oneself and others, presumably by accessing

common codes for perception and action (Prinz, 1997; Repp & Knoblich, 2004). Sensorimotor cues are especially informative for determining whether perceived events are the result of one's current actions. Detection of sensorimotor cues might be achieved either by comparing the predicted and actual consequences of actions (Frith et al., 2000) or by a dedicated who-system (Georgieff & Jeannerod, 1998). Although the present study focused on temporal cues in the auditory domain, it should be possible to develop comparable tasks in the visual domain. This would be an important next step in the further exploration of the psychophysics of agency.

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