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RESEARCH ARTICLE

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Does an auditory perceptual illusion affect on-line auditory action control? The case of (de)accentuation and synchronization

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Abstract Many recent studies have investigated whether visual (spatial) illusions affect visual (spatio-temporal) action control, with results that are far from simple. The present study asks the analogous question with regard to auditory temporal perception and action timing. The auditory illusion chosen for this particular study is the effect of increasing or decreasing the intensity of a tone in a sequence (i.e., accentuation or deaccentuation) on its perceived relative time of occurrence. The motor task is sensorimotor synchronization (finger tapping), specifically the automatic phase correction response to an advanced or delayed tone in a sequence. The strong hypothesis was that (de)accentuation would affect perceptual judgments of the tone's relative time of occurrence, but would have no effect at all on the phase correction response. The results of two experiments, if averaged across participants, confirm these predictions and furthermore suggest that individual perceptual and sensorimotor effects of (de)accentuation are uncorrelated. It is argued that perception and motor control in this case probably rely on different kinds of temporal information: relative versus absolute time of occurrence. Two unexpected findings complicate the results, however: the perceptual illusion was asymmetric, occurring only for delayed tones; and many individual participants did show significant differences in their phase correction response to accented and deaccented tones, although the direction of that difference varied.

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Introduction

Perception versus action control

A lively discussion is going on in the literature on whether action control is or is not sensitive to perceptual illusions. Although, perception-action dissociations were first observed more than two decades ago (e.g., Bridgeman et al. 1981; Bridgeman et al. 1979), the recent spate of research and discussions was stimulated by the report of Aglioti et al. (1995) that sensorimotor control of grasping is immune to the Titchener circles (size-contrast) illusion. (See Carey (2001), for a brief review.) This result seemed to provide direct support for the important theory of Milner and Goodale (1995) that visual perception rests on two separate systems, one associated with the ventral processing stream in cortex and being responsible for perception of objects and the other associated with the dorsal stream and being responsible for action control.

Meanwhile, the empirical evidence has grown increasingly complex. Whether or not a visual illusion affects action as much as it affects perception seems to depend, among other things, on the nature of the illusion (Milner and Dyde 2003), on perceptual task demands and attentional strategies (Franz 2001; Franz et al. 2000), on the aspect of an action that is being examined (Brenner and Smeets 1996; Jackson and Shaw 2000), and on the point in the time course of an action at which the relevant observations are made (Glover and Dixon 2001, 2002). The last-named authors have proposed that during an action there is a gradual progression from planning, which relies on rich perceptual and cognitive information, to on-line control, which is faster and more flexible but limited to local spatial information. For an extensive review of findings supporting this theory, followed by peer commentary, see Glover (2004).

As is so often the case in psychology, these exciting theoretical and empirical developments have occurred almost entirely within the domain of vision. One might ask, however, as Carey (2001) does, whether similar dissociations between illusory perception and action occur also in other modalities. Research on vision has been so vigorous not only because vision is arguably the most important sensory modality but also because there is strong evidence for two visual processing streams from anatomical, neurophysiological, and neuropsychological studies (see Milner and Goodale 1995). For other sensory modalities, this kind of research is much more limited, although evidence for two (and possibly more than two) auditory processing streams in monkeys has emerged from the anatomical and neurophysiological work of Rauschecker and colleagues (e.g., Rauschecker 1998; Rauschecker and Tian 2000; Romanski et al. 1999; see also Kaas and Hackett 1999, 2000) and has also received support in an fMRI study of humans (Alain et al. 2001). The functions of these two streams have been characterized in terms of 'what' and 'where' perception, in analogy to Ungerleider and Mishkin's (1982) attribution of these perceptual functions to the two visual streams. Milner and Goodale (1995), however, argued against that theory by proposing that the functional separation is really between perception and action control. Applying the Milner-Goodale perspective to audition, Kubovy and Van Valkenburg (2001) hypothesized that the auditory 'where' subsystem is in fact serving action control.

In nonhuman animals, auditorily guided action is generally limited to orienting, flight, and pursuit, with significant specializations occurring in some species, such as echolocation in bats. Two uniquely human actions that are guided by auditory feedback are music performance and speech production. It may be asked whether on-line control of these actions relies on different cortical processing pathways than conscious perception and judgment of music and speech. Clearly, this is an interesting question for neuroscience to address. However, a theoretical distinction between conscious perception and action control can be drawn regardless of whether these functions have been identified with anatomically or physiologically distinct brain structures. Behavioral studies of possible dissociations between these two functions need not wait for neuroscience to provide a structural foundation. On the contrary, they may provide paradigms and results that may prove useful in the search for relevant brain structures. The present study was conducted in that spirit.

Behavioral studies of functional dissociations between auditory perception and auditorily guided action are scarce. Two studies cited by Kubovy and Van Valkenburg (2001) in that connection probably do not constitute good examples: Deutsch and Roll (1976) found a dissociation between 'what' (pitch) and 'where' (localization) perception in a dichotic phenomenon known as the octave illusion, but that paradigm does not involve action. Moreover, Deutsch's interpretation has been challenged (Chambers et al. 2002, 2004a, 2004b; but see Deutsch 2004a, b, for counterarguments). Wynn (1977) attributed the bimodal distribution of a large sample of simple auditory reaction times (RTs) to two auditory pathways differing in transmission speed. Because both hypothetical pathways led to the same action, however, they were not considered to differ in function. Rather than reflecting different pathways, Wynn's results may be due to discrete temporal processing in a single neural system, with the separation between the RT distribution modes reflecting the underlying time quantum (Pöppel 1996, 1997). Genuine examples of an auditory perception-action dissociation may be provided by studies of adaptation to pitch-shifted feedback in whistling (Anstis and Cavanagh, 1979) and phonation (Burnett et al. 1998; Hain et al. 2000). The latter authors, in particular, have distinguished two adaptive responses to pitch shifts, one being fast and automatic and the other slower and probably voluntary. These responses may reflect automatic on-line action control and perceptually mediated cognitive action control, respectively, although perception of the feedback changes was not assessed directly.

Sensorimotor synchronization

Sensorimotor synchronization, specifically finger tapping in time with an auditory metronome, is an activity that requires continuous error correction based on sensory information and in that sense is auditorily guided. Mates (1994) distinguished between two control processes: phase correction and period correction. In the course of a subsequent application of this dual-process model, Repp (2001b) hypothesized that phase correction is an automatic on-line control process, whereas, period correction is a more conscious, perception-based process that is also involved in temporal planning. Empirical support for these claims has emerged from a series of recent synchronization studies.

Repp (2000, 2001a) showed that phase correction in response to timing perturbations in an auditory sequence is independent of participants' awareness of these perturbations or of the asynchronies they cause. Repp and Penel (2002) found similarly that phase correction is independent of conscious perception of timing perturbations in synchronization with visual sequences. These results complement findings in visual studies showing that a masked and hence not consciously perceived visual stimulus can nevertheless activate motor processes (e.g., Eimer and Schlaghecken 1998; Klotz and Neumann 1999). By contrast, period correction in synchronization depends on conscious detection of a tempo change in a sequence (Repp 2001b; Repp and Keller 2004). When participants are instructed not to react to timing perturbations in a sequence, they are unable to suppress phase correction (Repp 2002a, 2002c; Repp and Keller 2004), whereas period correction can be suppressed completely and can even be employed strategically to counteract involuntary phase correction (Repp and Keller 2004). These results provide support for the identification of phase correction with on-line action control, and of period correction with conscious perception and action planning, in accord with the theoretical distinctions in vision drawn by authors such Milner and Goodale (1995) and Glover (2004).

Several studies of sensorimotor synchronization have manipulated variables that proved to affect perception but not on-line action control (i.e., phase correction), and thus they may be considered as precursors to the present experiments. Repp and Keller (2004) diverted attention from a combined synchronization and detection task by having participants perform mental arithmetic at the same time. The additional task impaired detection of tempo changes in the auditory sequences, and it also reduced period correction in synchronization, but it did not affect phase correction. Repp (2002b) investigated the effect of preceding context on synchronization and detection tasks, performed separately or in combination: when an irregularly timed precursor sequence preceded a largely isochronous test sequence, detection of a deviation from regularity in the test sequence was impaired, but synchronization accuracy (variability) and phase correction in response to the perturbation were unaffected. Repp (2000, 2001a, 2002c) showed that, whereas perturbation magnitude affects detectability in a nonlinear way (the response function is typically sigmoid), the magnitude of the phase correction response varies linearly over the same range. The previous experiment that comes closest to the approach taken in the present study, Experiment 5 of Repp (2000), employed auditory sequences that started with tones of one pitch and later changed to tones of a higher or lower pitch. A positive phase shift (i.e., a lengthened inter-onset interval) was more difficult to detect when it occurred at the point of pitch change than when it occurred elsewhere in the sequence, but the pitch change had no effect on phase correction in synchronized tapping.

Although all these experiments demonstrated dissociations between perception and action control, none except perhaps the last one involved what one might call an auditory illusion. The perceptual effect of a pitch change on timing, which has been demonstrated previously (Thorpe and Trehub 1989; Thorpe et al. 1988), could indeed be regarded as a kind of auditory illusion: Repp (2000) suggested that the interval separating two groups of tones differing in pitch is perceived as relatively short because inter-group intervals are expected to be lengthened; this makes a small lengthening of the inter-group interval difficult to detect. But why does the pitch change not affect action timing as well? There are at least two possible answers: if perceiving an interval as relatively short means that the tone terminating the interval is perceived as being advanced in time, then the results obtained would suggest that action control has access to veridical onset times via a different processing stream. Alternatively, it could be argued that the perceptual illusion is restricted to intervals between event onsets and does not affect at all the perceived time of occurrence of the events, whereas action timing relies on those times of occurrence. The second interpretation seems more straightforward and is in the spirit of arguments in the visual literature that perception and action may rely on different kinds of information, but do not necessarily require different processing streams (Smeets and Brenner 1995; Smeets et al. 2002). There is one theory of timing judgment according to which perception of a change in interval duration arises not from a comparison with preceding intervals but from the detection of an asynchrony between the expected and actual times of occurrence of its terminal event (Large and Jones 1999; McAuley and Jones 2003). However, that theory does assume veridical perception of times of occurrence: it is the expected time that is inaccurate and causes a misjudgment.

The present study

To investigate further a possible dissociation between perception and action control at the behavioral level, the present study employed a different auditory illusion, namely the effect of a change in intensity (an accent) on perceived timing. This effect was first described over a century ago (see Woodrow 1909, who provides a detailed discussion and review of even earlier work) and was investigated more recently in a series of studies by Tekman (1995, 1997, 2001). The illusion is that the interval preceding an accented tone (Tekman used an intensity increase of 4.5 dB) is perceived as being lengthened relative to other intervals in a sequence. The cause of this perceptual distortion may lie in an internal model of rhythm production: when an accented tap is produced in a sequence of moderate tempo, the preceding interval is typically shortened while the following interval is lengthened (Billon and Semjen 1995; Billon et al. 1996; Piek et al. 1993; Semjen 1986). Perception of an accented tone in a sequence may activate an internal representation of these systematic effects in production, which in turn causes the interval preceding the accented tone to be perceived as relatively long when it is not actually shortened. The effect of a lowering of intensity (deaccentuation) does not seem to have been investigated in perception, and in production only at a very fast tempo (Semjen 1984), where the kinematics and their effect on timing may be quite different. The present study employed both increases and decreases in intensity of a critical tone in a sequence, which were expected to have opposite effects.

Participants were asked to synchronize finger taps with isochronous auditory sequences containing a single advanced or delayed event. This *event onset shift (EOS)* varied in direction (negative = advance, positive = delay) and magnitude. Participants were instructed not to react to the EOS (if they detected it) and to continue tapping regularly. Despite such instructions, an involuntary shift of the following tap in the same direction as the EOS, termed the automatic *phase correction response (PCR)*, is typically observed (Repp 2002a).[1] After each sequence, participants had to report whether or not they had detected an EOS and what its direction was. On some trials, the shifted tone was accented (i.e., increased in intensity). It was expected that this accentuation would make a negative EOS (i.e., an advancement of the critical tone) more difficult to detect and a positive EOS (i.e., a delay of the critical tone) easier to detect, relative to their detection in sequences containing no accented tone. (Note that, in terms of signal detection theory, these predictions concern perceptual biases, not increases in sensitivity. Thus, increases in correct responses may go along with increases in false alarms.) However, if there is a dissociation between perception and action control, no corresponding shift should occur in the PCR. On other trials, the shifted tone was deaccented (i.e., lowered in intensity). Here, the opposite effect on perception was expected, but again it was predicted that there would be no effect on the PCR. An effect of the auditory illusion on the PCR would show up as a difference in intercepts between the (typically linear) functions relating PCR magnitude and EOS magnitude for unaccented and (de)accented tones. Two similar experiments were conducted which differed only in details of design.

Experiment 1

Methods

Participants

The participants included seven paid volunteers (5 women, 2 men, aged 18–30) and the author (age 58 at the time). All were regular participants in synchronization experiments and, with one exception, had extensive musical training: three were professional musicians (violin, viola, clarinet), and four others had studied piano for at least 10 years; one participant had had just a few years of basic piano lessons. Using musically trained and practiced individuals helped reduce variability in the data and made the difficult dual-task paradigm feasible. All paid participants had signed a consent form approved by the local institutional review board; the study was thus conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Materials

Each auditory sequence consisted of 10 high-pitched tones (E_7, about 2,640 Hz) which were produced on a Roland RD-250s digital piano under control of a program written in MAX 3.0 running on a Macintosh Quadra 660AV computer.[2] Participants listened over Sennheiser HD540 II headphones at a comfortable intensity. The basic inter-onset interval (IOI) between tones was 500 ms. An event onset shift (EOS) always occurred on the seventh tone, which was displaced by an amount (Δt) ranging from -30 to -10 ms and from $+10$ to $+30$ ms in steps of 5 ms, so that the IOI terminated by that tone was shortened or lengthened by Δt, while the following IOI was changed in a compensatory fashion. Trials with $\Delta t = 0$ were also included. In half the trials (baseline), the critical seventh tone had the same intensity as all other tones, which corresponded to a MIDI key velocity setting of 60. In the other half, depending on the condition, the critical tone was either accented (+acc, MIDI velocity of 80) or deaccented (–acc, MIDI velocity of 40). According to acoustic measurements conducted some time ago (see Repp, 1997: Figure 1), these differences are equal to about ± 5 dB. In each accent condition, the 22 sequences (11 Δt values $\times$ 2 critical-tone intensities) were arranged into 11 different random orders (blocks), the first of which served as practice.

Procedure

Participants came for two sessions, which were typically separated by one week and lasted about 50 min each. One session included the baseline and +acc conditions and the other, the baseline and –acc conditions. The order of the two sessions was counterbalanced across participants. Participants were instructed to tap in synchrony with each sequence, starting with the third tone. They were told that a deviation from regular timing (an EOS) might occur on the seventh tone of a sequence, but that they should not react to it and should continue to tap regularly. If they noticed that they had reacted to an EOS, they were to repeat that trial immediately by clicking a "repeat" button on the computer screen. Participants were familiar with this task from earlier experiments. They tapped with the right index finger on a Roland SPD-6 electronic percussion pad which they held on their lap. The sound output of the percussion

[1] The automatic PCR is typically smaller than the "ordinary" PCR obtained when participants are merely instructed to stay in synchrony, particularly when the EOS is large enough to be detected (Repp 2002a, c). The purpose of the instructions given here (i.e., not to react to an EOS) was to elicit the purely automatic component of the PCR, which is assumed to reflect phase correction only and is hypothesized to be independent of conscious perception. The ordinary PCR includes a consciously controlled component of phase correction or perhaps even a contribution of period correction, which depends on conscious perception (Repp 2002b; Repp and Keller 2004).

[2] Due to a peculiarity of this setup, the tempo of the output was about 2.4% faster than specified in the MIDI instructions, as determined in earlier acoustic waveform measurements. The participants' key presses were registered at a correspondingly slower rate. All millisecond values are reported as they appeared in the MAX environment.

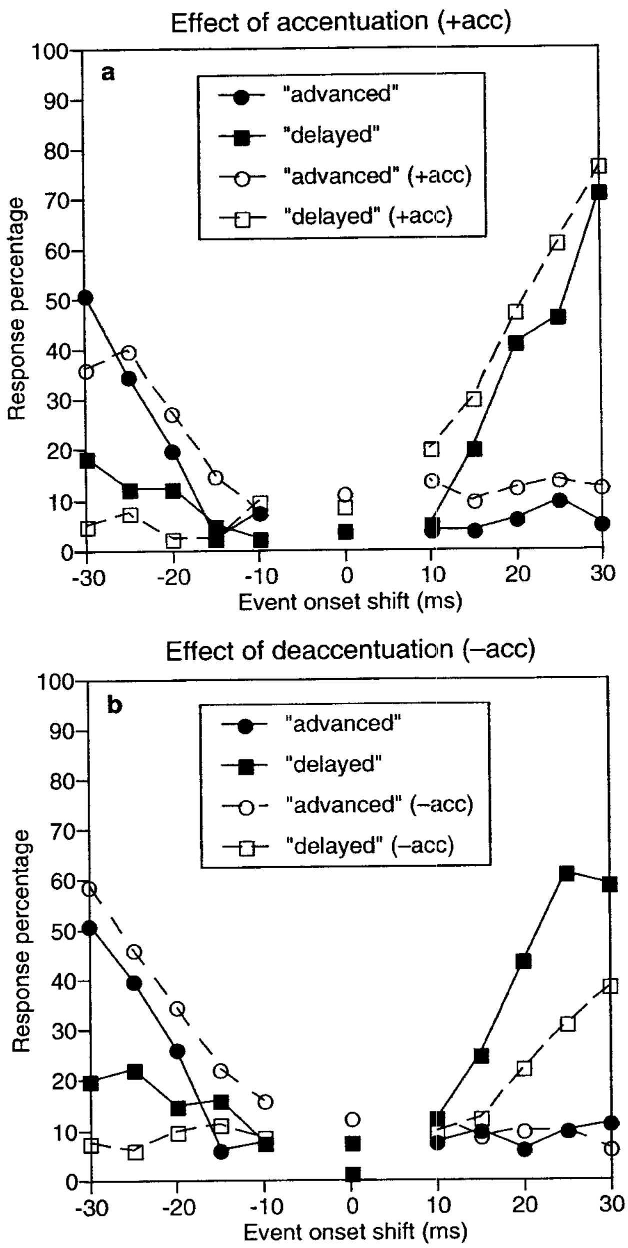

Fig. 1 Detection results of Experiment 1. Percentages of "advanced" and "delayed" responses are shown for baseline and +acc conditions (*panel a*) and for baseline and –acc conditions (*panel b*)

pad was not used, but there was some direct auditory feedback from each tap (a thud).

In addition, participants were required to report after each trial whether it had contained an EOS and what its direction was. They were informed that the critical seventh tone would be (de)accented on half the trials. The (de)accentuation was described as being irrelevant to the task and independent of the EOS. Three keys on the computer keyboard were labeled "advanced," "no change," and "delayed." Pressing one of these response keys triggered the next sequence after a delay of 2 s.

Results and discussion

Detection accuracy

The results of the detection task are shown in Fig. 1. Overall, detection accuracy was poorer than expected on the basis of earlier EOS experiments of similar design (Repp 2002a), which suggests that the presence of intensity variation in the present experiment interfered with the detection of timing deviations, even in baseline sequences where all tones were equal in intensity. The upper panel compares the response functions for the +acc condition with those for the baseline condition from the same session. The functions which increase steeply with absolute EOS magnitude represent correct responses, the flatter functions represent incorrect responses, and the data points for EOS = 0 represent false alarms. It was expected that accentuation would cause a perceptual bias in favor of "delayed" responses and thereby would make a positive EOS (a delayed tone onset) easier to detect, and a negative EOS (an advanced tone onset) harder to detect. The first prediction was confirmed, but the second was not, except at the largest negative Δt. Moreover, contrary to the expected bias, accentuation seemed to increase incorrect "advanced" responses but decrease incorrect "delayed" responses, and false alarms were increased for both responses. The lower panel compares the response functions for the –acc condition with those for the baseline condition from the same session. Here it was expected that deaccentuation would cause a perceptual bias in favor of "advanced" responses and thus would make make a negative EOS easier to detect, and a positive EOS harder to detect. The data confirmed both predictions. The false alarms, too, showed corresponding tendencies, and although incorrect "advanced" responss were not increased, incorrect "delayed" responses were reduced relative to baseline.

To test the consistency of the differences in correct responses across participants, a 2 × 5 × 2 repeated-measures ANOVA was conducted on the percentages of correct responses in each session, with the variables of EOS direction (negative, positive), EOS magnitude ($|\Delta t|$, with $\Delta t = 0$ excluded), and accentuation (+acc or –acc vs. baseline). The effect of interest was the EOS direction x accentuation interaction. It was significant for –acc, $F(1,7) = 34.2, p < 0.001$, but not for +acc, $F(1,7) = 0.6$. Thus, surprisingly, the predicted perceptual effect was reliable only in the condition in which it was tested here for the first time (–acc), but not in the condition (+acc) in which it had been obtained in earlier studies. Methodological differences could be responsible for that (see General Discussion).

Apart from the main effect of EOS magnitude, which was obviously significant and reflected the increase in correct detection responses as EOS magnitude increased, two additional effects reached significance in the analysis of the +acc session: the main effect of EOS direction, $F(1,7) = 7.4, p < 0.03$, and the EOS direction x EOS magnitude interaction, $F(4,28) = 4.7$, $p < 0.02$, $\epsilon = 0.70$ (Greenhouse-Geisser epsilon). Both reflect the fact that delayed tone onsets were easier to detect than advanced onsets, an asymmetry that has been observed previously (Repp 2002a). This asymmetry was also evident in the baseline condition of the –acc session, but in the –acc condition itself it was counteracted by the effect of deaccentuation and therefore was not significant overall in that session.

An alternative way of analyzing the detection data is to compare the +acc and –acc conditions directly while omitting the baseline data. It can be seen by comparing the two panels of Fig. 1 that there was little difference between these two conditions with regard to the detectability of advanced tone onsets, whereas delayed tone onsets were easier to detect when the tone was loud (+acc) than when it was soft (–acc); moreover, that difference increased with delay magnitude. In the new ANOVA, this pattern of results was reflected in a significant EOS direction x EOS magnitude x accentuation interaction, $F(4,28) = 4.93$, $p < 0.03$, $\epsilon = 0.53$. The EOS direction x accentuation interaction was also significant, $F(1,7) = 9.75$, $p < 0.02$, but the main effect of accentuation was not.

Phase correction responses

The PCR results are shown in Fig. 2. Each panel shows the average magnitude of the PCR as a function of EOS magnitude, separately for the baseline and +acc (upper panel) or baseline and –acc (lower panel) conditions. The relationships between PCR and EOS were strongly linear, as expected. An effect of accentuation (+acc) on the PCR would be reflected in an upward shift of the regression line, whereas an effect of deaccentuation (–acc) would be reflected in a downward shift. In both cases, however, there were only minimal differences in intercept which were nonsignificant in paired-sample *t*-tests on the intercepts of individual participants' PCR functions. Unexpectedly, however, deaccentuation was associated with a shallower slope of the regression line (0.51 versus 0.71), $t(1,7) = 5.4$, $p < 0.001$, whereas, accentuation did not cause a significant difference in slope from baseline (0.64 versus 0.62).[3] In a direct comparison of the +acc and –acc conditions, however, the slope difference did not reach significance, $t(1,7) = 1.83$, $p < 0.11$. These findings were confirmed in three 2 x 11 repeated-measures ANOVAs on the PCR data, with the variables of accentuation (+acc vs. baseline, –acc vs. baseline, or +acc vs. –acc) and Δt. The main effect of accentuation, which corresponds to the difference in intercepts, was nonsignificant in all three ANOVAs. The Accentuation x Δt interaction, which corresponds to the difference in slopes, was significant only in the –acc vs. baseline ANOVA, $F(10,70) = 3.47$, $p < 0.02$, $\epsilon = 0.41$. The main effect of Δt, which corresponds to the difference in slope from zero, was trivially significant in all analyses.

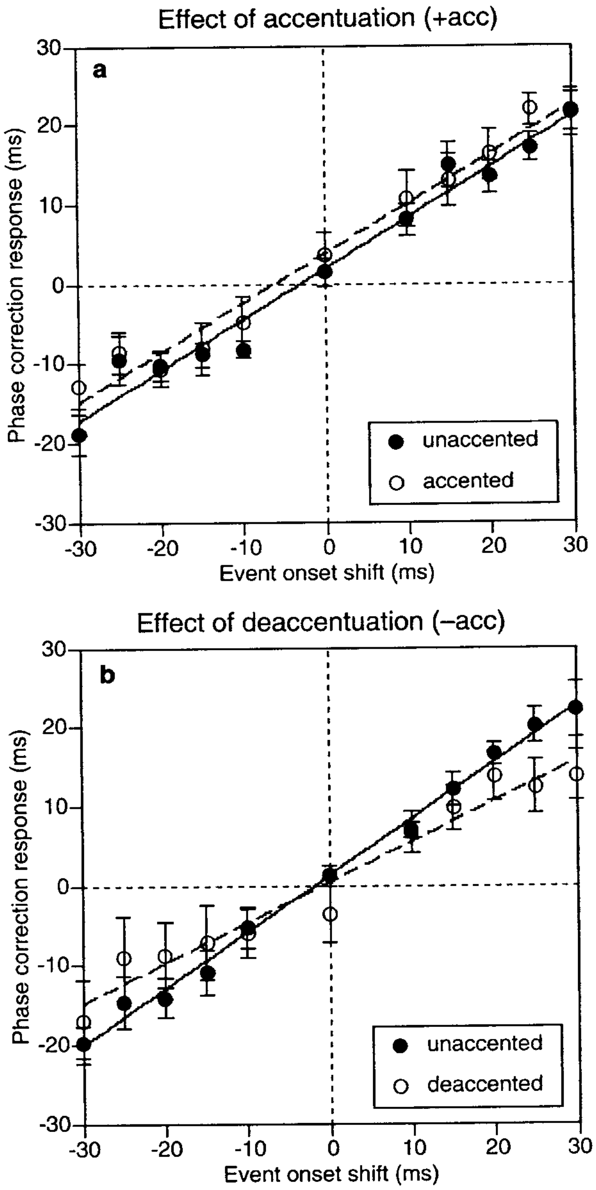

Fig. 2 Phase correction response (PCR) results of Experiment 1. Mean PCR is shown as a linear function of event onset shift magnitude for unaccented (baseline) and accented (+acc) conditions (*panel a*) and for unaccented (baseline) and deaccented (–acc) conditions (*panel b*)

Individual results

The similar intercepts of the functions in Fig. 2 lend support to the hypothesis that on-line action control is not affected by (de)accentuation of the critical tone.

[3] All slopes were a good deal steeper than expected: The average slope for the same Δt values—although embedded in a context of larger Δt values—in a previous experiment (Repp 2002c) had been .41. In other words, participants responded quite vigorously to the EOSs, even though they had been instructed to ignore them.

Table 1 Differences in intercept (diff, in ms), as well as F(1,198)[a] and *p* values for the main effect of accentuation in ANOVAs on individual PCR data in Experiment 1

Ptcpt	+acc vs. baseline			−acc vs. baseline			+acc vs. −acc		
	diff	F	*p*	diff	F	*p*	diff	F	*P*
B.R.	−3.87	10.51	<0.001	2.45	4.72	0.04	−4.29	14.61	<0.001
H.R.	2.03	0.85	0.36	−10.46	19.48	<0.001	13.69	36.29	<0.001
N.K.	−12.84	30.09	<0.001	10.46	16.12	<0.001	−20.06	65.84	<0.001
S.L.	3.66	1.91	0.17	−5.62	3.65	0.06	10.58	14.95	<0.001
S.K.	10.62	16.76	<0.001	−0.10	0.00	0.97	10.05	13.20	<0.001
T.S.	7.84	5.13	0.03	−2.78	0.62	0.44	10.28	6.89	0.009
V.T	2.64	2.49	0.12	−8.39	16.67	<0.001	6.73	13.15	<0.001
V.N.	5.25	4.64	0.04	7.67	10.46	<0.001	0.00	0.00	1.000

[a]Error degrees of freedom for T.S. in the three comparisons were 164, 181, and 172, respectively, because a number of trials contained missing taps and had to be discarded

However, some individual participants did show rather large differences in intercept. These differences were tested for significance by conducting a 2 x 11 ANOVA on each participant's individual PCR data. The ten repetitions of each sequence type were considered a random variable and thus provided a pooled error term with a large number of degrees of freedom. Table 1 shows the individual intercept differences as well as the F and *p* values for the main effect of accentuation in the individual ANOVAs. In the +acc condition compared to baseline, three participants showed a significant intercept difference in the positive direction, which is consistent with the predicted perceptual bias, but two showed a significant difference in the opposite (negative) direction. In the −acc condition versus baseline, two participants showed a significant difference in the negative direction, which is consistent with perception, but three showed a significant difference in the opposite (positive) direction. The Δt x Accentuation (−acc vs. baseline) interaction, representing the slope difference, was nonsignificant for all participants, even though it had been significant in the overall ANOVA. The main effect of Δt was significant in all individual analyses.

When the individual results for the +acc and −acc conditions were compared directly (last three columns of Table 1), even more reliable differences in intercept emerged for 7 of the 8 participants. Five of them showed a difference in the expected (positive) direction, whereas two (one of them being the author, an amateur pianist, the other an amateur percussionist) showed a negative difference. The Δt x Accentuation interaction, which assesses the difference in slopes, was also significant for these last two participants and reflected a shallower slope of the −acc function. These heterogeneous individual results indicate that the effects of accentuation on action control are more complex than the average results suggest.

Relationship between detection accuracy and PCR results

For each participant, a measure of the influence of (de)accentuation on detection accuracy was obtained. First, the difference between the average percent correct scores for positive and negative Δt values (i.e., a difference score) was computed, and then detection scores were calculated by subtracting the baseline difference score from the +acc or −acc difference score, or the −acc from the +acc difference score. The detection score thus corresponded to the EOS direction x accentuation interaction in the ANOVA. For each of the three comparisons among conditions, the correlation between the individual detection scores and the individual intercept differences was then computed. The correlations were 0.05 (−acc vs. baseline), 0.05 (+acc vs. baseline), and 0.23 (+acc vs. −acc), all nonsignificant. A correlation of at least 0.71 would have been needed for significance. Although these statistics obviously have low power because of the small number of participants, they do suggest that the perceptual effects of (de)accentuation are independent of any effects of accentuation on action control.

Experiment 2

Although the average results of Experiment 1 support the main hypothesis that (de)accentuation would affect perception but not on-line action control, several unexpected findings complicate the picture. First, detection performance was poorer than expected, and this may have affected the reliability of the detection results. In Experiment 2, therefore, the range of EOS magnitudes was increased. Second, the expected effect of (de)accentuation on detection of EOSs was decidedly asymmetric in Experiment 1, affecting only the detection of delays. Experiment 2 re-examined that asymmetry by omitting the baseline condition and intermixing the +acc and −acc conditions, which had been presented in separate sessions in Experiment 1. Two further unexpected results of Experiment 1 also seemed to warrant replication: the slope difference between the PCR functions for the +acc and −acc conditions, and the presence of significant intercept differences between the PCR functions for individual participants. About one year elapsed between Experiments 1 and 2.

Methods

Participants

The participants included seven paid volunteers (3 men, 4 women, aged 18–35) and the author (B.R., now 59 years old). Two of them (S.K. and B.R.) had participated in Experiment 1. All were regular participants in synchronization experiments and, with one exception, had extensive musical training: four were professional musicians (violin x 2, viola, clarinet), two were amateur percussionists, and one (B.R.) an amateur pianist; one had had 5 years of piano lessons but did not play any more. All paid participants had signed a consent form approved by the local institutional review board; the study was thus conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Materials

The sequences were the same as in Experiment 1, except for the following changes. The EOS values (Δt) ranged from –50 to +50 ms in steps of 10 ms. The critical tone was either accented (+acc) or deaccented (–acc). The 22 trial types (11 Δt values x 2 accentuation conditions) were presented in 11 different randomizations (blocks), the first of which served as practice.

Procedure

The procedure was the same as in Experiment 1, except that participants were alerted to the fact that the critical tone would always be either louder or softer than the surrounding tones.

Results and discussion

Detection accuracy

Figure 3 shows the detection results. With the extended range of EOSs, somewhat higher correct response percentages were achieved, but performance was still far from perfect even at EOSs of ±50 ms. One participant (the one with the least musical training) performed almost randomly in the detection task. Nevertheless, the average data confirm the asymmetric findings of Experiment 1: a large difference between the +acc and –acc conditions in the predicted direction was present for positive EOSs (delayed tone onsets), but there was no difference for negative EOSs (advanced tone onsets). Although delays were easier to detect when the tones were accented than when they were deaccented, there was no parallel increase in false-alarm or incorrect "delayed" responses, which makes the results look more like a difference in sensitivity than one in perceptual bias.

A 2 x 5 x 2 repeated-measures ANOVA on the correct response percentages with the variables of EOS direction, EOS magnitude ($|\Delta t|$, with Δt = 0 excluded), and accentuation yielded a significant main effect of accentuation, $F(1,7) = 5.80$, $p<0.05$. Surprisingly, however, the direction x accentuation interaction did not reach significance, $F(1,7) = 4.19$, $p<0.08$, nor did the triple interaction, $F(4,28) = 2.67$, $p<0.06$, $\epsilon = 0.74$. This indicates considerable individual differences in the de-

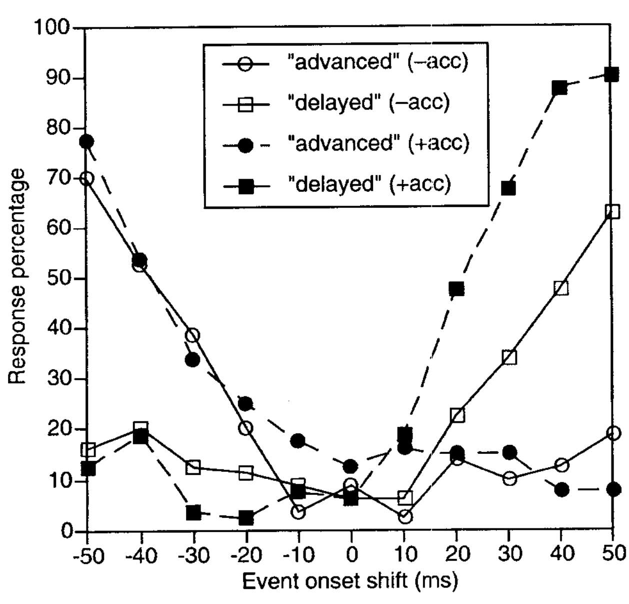

Fig. 3 Detection results of Experiment 2. Percentages of "advanced" and "delayed" responses are shown for +acc and –acc conditions

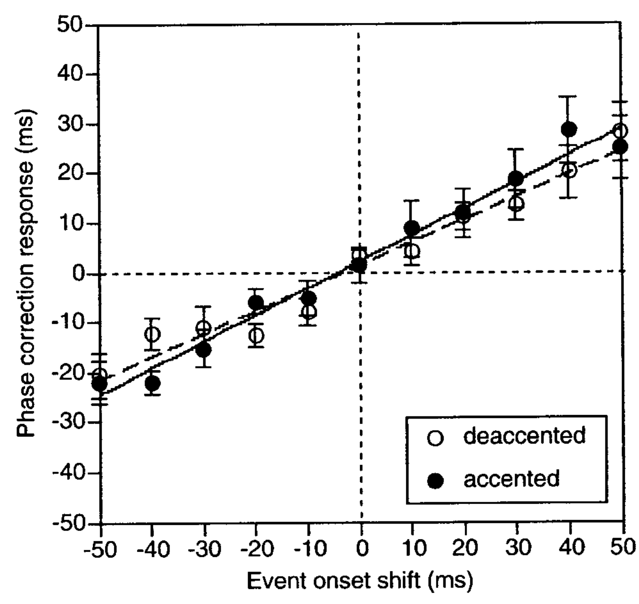

Fig. 4 Phase correction response (PCR) results of Experiment 2. Mean PCR is shown as a linear function of event onset shift magnitude for accented (+acc) and deaccented (–acc) conditions

gree of asymmetry of the perceptual effect. Omitting the participant who had nearly random data did not change the statistics much. The main effect of EOS magnitude was highly significant, of course.

Phase correction response

The PCR data are shown in Fig. 4. There was again a linear relationship between PCR magnitude and EOS magnitude. The functions for both accentuation conditions had intercepts near zero, as predicted. Although the –acc function had a slightly more shallow slope than the +acc function, this difference was smaller than in Experiment 1. Indeed, neither the difference between intercepts nor that between slopes was close to significance in paired-sample *t*-tests. A 2 x 11 repeated-measures ANOVA on the PCR data likewise showed no significant main effect of accentuation, although the accentuation x Δt interaction (corresponding to the slope difference) came close to being significant, $F(10,70) = 2.90$, $p < 0.06$, $\epsilon = 0.30$.

Individual results

The results for individual participants are shown in Table 2. The two participants who had also been in Experiment 1, B.R. and S.K., showed very similar intercept differences as previously, although the difference did not reach significance here for B.R. Only one other participant (L.M.) showed a significant intercept difference, but that difference was very large and contrary to predictions based on perception, like that of N.K. in Experiment 1 (Table 1).

Relationship between detection accuracy and PCR results

A detection score was calculated for each participant, as in Experiment 1. Its correlation with the intercept difference between the PCR functions was 0.29 and thus far from significance.

Table 2 Differences in intercept (diff, in ms), as well as $F(1,198)^a$ and *p* values for the main effect of accentuation in ANOVAs on individual PCR data in Experiment 2

Ptcpt	+acc vs. –acc		
	diff	F	*p*
B.R.	–2.69	3.12	0.08
D.S.	4.36	2.96	0.09
J.W.	0.52	0.41	0.53
L.M.	–20.37	40.26	<0.001
M.K.	2.94	1.39	0.24
S.C.	3.89	1.54	0.22
S.K.	9.46	15.73	<0.001
T.L.	1.09	0.13	0.72

[a]Error degrees of freedom were slightly smaller for some participants because some trials were skipped by mistake

Combined analysis of Experiments 1 and 2

Because the statistics across participants had relatively low power in each experiment, the results of the two experiments were also analyzed in combination. The baseline data from Experiment 1 were excluded, and the data of the two participants who had served in both experiments were averaged across experiments, yielding a total *N* of 14. The EOS magnitude factor could not be included in the analyses because of the different EOS ranges in the two experiments.

In the analysis of the correct detection responses, the accentuation x EOS direction interaction was significant, $F(1,13) = 9.46$, $p < 0.009$, confirming the asymmetric effect of accentuation on detection. The intercepts of the PCR functions were not significantly different in a *t*-test, $t(13) = 0.52$, and the slope difference also fell short of significance, $t(13) = 2.02$, $p < 0.07$. The correlation between the individual detection scores and intercept differences was 0.23 and nonsignificant, suggesting no relation between perception and action control. (A correlation of .53 would have been needed for significance.)

General discussion

Does an auditory illusion, such as the influence of an intensity change on perceived timing, affect on-line action control? The answer from the present experiments is a qualified "no". The two results supporting this conclusion are that (1) on average there was no effect of (de)accentuation on phase correction, as reflected in the timing of the next tap (the intercept of the PCR function), and (2) there was no significant correlation between the effects of (de)accentuation on perception and on action timing at the individual level.

Against this general conclusion stands the finding that a number of participants did show significant effects of (de)accentuation on action timing. Of the 14 participants involved in the two experiments, five showed a significant positive intercept difference between the +acc and –acc PCR functions, which is the kind of difference one would expect if perception influenced action. Two participants, however, showed large *negative* intercept differences, and a third participant (the author), a small one. These individual effects and their difference in direction are difficult to explain. For the two individuals who participated in both experiments, the effects appeared to be replicable. It should be noted that the individual ANOVAs had much greater statistical power than the overall ANOVAs, so that some relatively small individual effects reached significance. Still, some of the individual effects are too large to be overlooked.

The effects of (de)accentuation on perceptual judgment, too, were quite variable at the individual level and not as consistent overall as had been expected. One reason for this may have been that there was only a single (de)accented tone in each sequence. Tekman

(2001) found that accentuation had a much larger effect on detection accuracy (compared to a baseline condition) when the accented tones occurred repeatedly at regular intervals during the sequence than when they occurred at random intervals. Although, the position of the (de)accented tone in the present sequences was constant and hence predictable, the fact that only a single critical tone was present may have attenuated the perceptual effect. Another methodological difference is of potentially greater importance, however: The temporal perturbation to be detected in Tekman's studies was a phase shift, which means that only the interval preceding the critical tone changed in duration, whereas in the present experiments it was an EOS, which means that the interval following the critical tone changed as well, in a complementary fashion. Although the present task required a judgment of whether the critical tone had occurred early, on time, or late—an aspect of the stimulus sequences that is independent of whether the perturbation is a phase shift or an EOS—participants may well have based their judgments on the perceived relative duration of the preceding interval. (Tekman's instructions referred to interval durations directly.) If the judgments were interval-based, the fact that two intervals changed in duration may have been a complicating factor in the present study. In defense of the present methodology, it should be said that previous perceptual studies have shown little difference in the detectability of phase shifts and EOSs (Friberg and Sundberg 1995; Repp 2001a, 2002a; Schulze 1978), and that accentuation of taps in production at a moderate tempo has temporal effects that resemble more an EOS than a phase shift (Billon and Semjen 1995; Billon et al. 1996). Nevertheless, a replication of the present study using phase shifts instead of EOSs would be worthwhile.

An unexpected asymmetry emerged in the perceptual results: A delayed tone onset was easier to detect when the critical tone was loud than when it was soft, but an advanced tone onset was not affected by the relative intensity of the critical tone, at least when the –acc and +acc conditions were compared directly. Tekman (2001) conducted a signal-detection-theory analysis of the two-alternative (same–different) detection responses in his study and found different asymmetries in the effect of accentuation on sensitivity and response bias measures. Sensitivity was affected only when the critical tone was advanced (being poorer with accented than with unaccented tones), but response bias was affected only when the critical tone was delayed (fewer "different" responses with accented than with unaccented tones). Neither of these asymmetries is in agreement with the present findings, which are also unclear as to whether the effect of (de)accentuation on perception of delays was primarily a change in sensitivity or in bias. For a rigorous signal-detection analysis, a much larger amount of data would have been needed (cf. Tekman 2001). The asymmetric perceptual results also seem inconsistent with the explanation based on action knowledge suggested in the Introduction.

Another unexpected finding, the tendency toward a shallower slope of the –acc PCR function relative to the +acc PCR function, is much easier to explain. It suggests that soft tones are somewhat less salient for action control than loud tones. A recent study (Repp in press) found this also to be the case in a target-distractor synchronization paradigm.

Why several participants exhibited a PCR-like reaction to the mere occurrence of a soft or loud tone, independent of whether it was phase-shifted or not (i.e., the intercept difference between individual PCR functions), remains a mystery, especially since the direction of the effect was not consistent across participants. It seems to constitute an idiosyncratic reaction to a change in relative tone intensity that is apparently unrelated to the effect of accentuation on perceived timing.

If the average results are accepted as evidence for a dissociation between perception of timing and action timing, it may be asked how they should be interpreted: do they suggest that action control has access to different, more veridical timing information than perception does, and thus that perception and action rely on different processing streams? Or do they suggest that perception and action rely on different forms of temporal information? An intermediate possibility is that there is a processing hierarchy for temporal information, with information for action control being obtained at an early stage and information for conscious perception at a later stage.

Perceptual judgments about timing necessarily are relative: To judge whether a tone has occurred early, on time, or late, it must be compared to a temporal expectation that depends on the preceding context (McAuley and Jones 2003). In most circumstances, as in the present experiment, this is equivalent to perceiving a local change in IOI duration or tempo: a tone sounds early if the IOI preceding it is shorter than even earlier IOIs. However the actual judgment process is conceptualized, it is always based on a relation between the time of occurrence of the critical tone and some other point(s) in time, which is to say it is based on one or more *intervals*. Phase correction in sensorimotor synchronization is also commonly thought to be based on interval information, namely on the asynchrony between a tap and a sequence event (e.g., Aschersleben, 2002; Vorberg and Schulze 2002). Alternatively, however, it may be thought of as a form of *phase resetting* with reference to the time of occurrence of the last tone and/or the last tap (Hary and Moore 1985, 1987). In the latter case, reference is made to one or more *time points*, not to an interval. This would be sufficient to account for the observed dissociation between perception and action control. Even if the perceived asynchrony, an interval, served as the basis of phase correction, it is a rather different kind of interval than the IOIs of a sequence: It is at least partially cross-modal (between a tap—a complex of kinesthetic, tactile, auditory, and visual information—and a tone), and it is generally much shorter than sequence IOIs. A (de)accented tone may well affect IOI perception and yet have no effect at all on asynchrony perception. In other words, (de)accentuation may affect the perceived interval between two tones without affecting the perceived time of occurrence of either tone. This interpretation would be consistent with the observation that perception and action often rely on different kinds of temporal information, one of which may be affected by the experimental manipulation, whereas the other may not be (Smeets and Brenner 1995; Smeets et al. 2002). The present results therefore neither contradict nor provide direct support for the hypothesis that there are different processing streams for perception and action in audition.

It is not inconceivable that the relative intensity of a tone also affects its perceived time of occurrence: A loud tone may be processed more quickly than a soft tone and thus reach awareness sooner. However, note that the direction of this effect would be contrary to the asymmetric effect of (de)accentuation on perceived timing. Therefore, this hypothesis is not helpful in explaining any of the present results.

One important difference between the present paradigm and studies using visual illusions and pointing or grasping tasks should be noted. In the latter studies, visual information is usually available continuously to guide action, and it is often the increasing reliance on local spatial information that reduces the effect of the original perceptual illusion on action (see e.g., Glover 2004). In the present study, the auditory timing information was discrete, and no gradual transition from one kind of information to another was possible. Therefore, the perceptual illusion and the information used for action control must have been dissociated from the beginning.

In summary, the present findings support the hypothesis that perception and action control can be dissociated in the auditory modality. They do not lead to any firm conclusions about the exact way in which this dissociation comes about, but it is suggested that perception and action in the case studied rely on different forms of temporal information. The study also raises the specter of individual differences, which it would be well to consider routinely in studies of this sort, as findings are not always as simple as they appear in average data.

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