The impact of pitch on tempo-spatial accuracy and precision in intercepting a virtually moving ball

J. Walter Tolentino-Castro[1], Anna Schroeger[2], Rouwen Cañal-Bruland[2], and Markus Raab[1,3]

[1] Department of Performance Psychology, Institute of Psychology, German Sport University Cologne

[2] Department for the Psychology of Human Movement and Sport, Institute of Sport Science, Friedrich Schiller University Jena

[3] School of Applied Sciences, London South Bank University

Author Note

J. Walter Tolentino-Castro https://orcid.org/0000-0002-4752-5571
Anna Schroeger https://orcid.org/0000-0001-9876-8322
Rouwen Cañal-Bruland https://orcid.org/0000-0002-7731-0934
Markus Raab https://orcid.org/0000-0001-6546-1666

The project was supported by the German Research Foundation (DFG) with two grants awarded to Markus Raab (RA 940/15-2) and Rouwen Cañal-Bruland (CA 635/2-2).

Correspondence concerning this article should be addressed to Dr. Walter Tolentino-Castro, Department of Performance Psychology of the Institute of Psychology at the German Sport University Cologne, am Sportpark Müngersdorf 6, 50933, Köln, Germany. Email: w.tolentino.castro@gmail.com

Abstract

In two experiments, horizontal and vertical orientated sounds moved in parabolas. Participants had to touch a screen to indicate where and when a virtual moving ball would cross a visible line. We predicted that due to the sensitivity of the auditory system to temporal information, manipulations of pitch should affect temporal errors more than spatial errors. Stimuli were sound sources at five different pitches moving along a parabola produced through loudspeakers mounted around a touch screen. Results showed pitch effects on spatial constant and spatial variable errors when the parabola was horizontally oriented (Exp. 1), and on temporal constant errors in vertically oriented parabolas (Exp. 2). We conclude that temporal and spatial precision in interception tasks were affected differently by pitch manipulations and require consideration in future studies when assessing the impact of auditory information on virtually catching moving balls.

Keywords: auditory stimuli, accuracy, precision, interception task, spatial error, temporal error

The impact of auditory pitch on temporal and spatial precision in intercepting a virtually moving ball

Catching and intercepting a ball is a highly complex and difficult task; in fact, it is considered one of the most challenging tasks in human motor performance (Brenner et al., 2013; López-Moliner et al., 2010; Ondobaka et al., 2017). Yet, soccer star Christiano Ronaldo can score even in complete darkness (see https://www.youtube.com/watch?v=aoScYO2osb0). This example highlights that judging the location of a ball is possible even if visual information is temporarily occluded (see Savelsbergh et al., 1993, for evidence regarding ball catching). How people manage to accurately deal with an interception task when only acoustic information is available is not well researched yet, in particular, when compared to the large number of studies on vision in interception (but see Komeilipoor, et al., 2015; Rosenblum et al, 1987). What is known, however, is that seeing and hearing affect temporal and spatial judgments differently in laboratory studies (O'Connor & Hermelin, 1972). Recent empirical findings from blind participants suggest that they tend to lateralize head movement for static and moving stimuli (Vercillo, Tonelli, & Gori, 2017), more precisely they spatially over/underestimate sound location. Whereas biases in sound produce spatial errors, less is known about how temporal precision in interception changes when auditory stimuli are manipulated. Aiming to scrutinize to what degree the auditory system is sensitive to temporal information in interception tasks (Recanzone, 2009), we designed the current study.

More specifically, in the present study we tested whether manipulating auditory information would have differential effects on spatial and temporal precision (standard deviation of participants' errors) and accuracy (mean of participants' errors) in intercepting virtual moving balls in two experiments.

It is undisputed that auditory stimuli play an important role in human perception (Altieri et al., 2015; Licklider, 1951), but empirical evidence for interception tasks is limited, as auditory information in catching or batting movements are not often studied (but see O’Brien et al., 2020; Sors et al., 2017). A few studies suggest that interception performance deteriorates when auditory stimuli are removed (e.g., Takeuchi, 1993). Further, the importance of auditory information in tasks involving anticipation of moving stimuli (e.g., the landing location of a tennis ball) has also been supported by empirical evidence (Cañal-Bruland et al., 2018; Müller et al., 2019). However, it remains to be determined how changes in sound alter (motor) interception performance (Rinaldi et al., 2016). A systematic manipulation of auditory information in interception tasks would illuminate if temporal and spatial perceptions are sensitive to change in acoustic information (Loeffler et al., 2018). We predict that manipulating sound sources will have a greater impact on temporal errors than spatial errors, as has been shown in temporal underestimations of perceptual time-to-arrival judgments (Gordon et al., 2013).

What auditory information can be used when intercepting moving balls? This question, as discussed above, has not been well studied (see Gray, 2009; Onishi et al., 2018), but it is known that auditory stimuli have multiple dimensions, such as noise type, wave form, intensity and pitch (Susini et al., 1999). Sounds, therefore, differ in the auditory attributes that can affect their perceptual quality and may impact interception performance and judgments (O’Brien et al., 2020; Sors et al., 2017). We illustrate this for the task we used in the current studies: a virtual ball moving in a parabola. The virtual ball produces sound sources on a touch screen; we manipulated the pitch and virtual ball direction relative to the perceiver.

Regarding movement direction of sound source, it is known that the orientation of a stimulus influences perceptual judgments (Neuhoff, 2016). For instance, it has been suggested that spatial precision of perceptual judgments differs when the auditory stimulus is horizontally (e.g., left to right) versus vertically (e.g., top to bottom) oriented (Grantham et al., 2003; Weger et al., 2016). When intercepting moving balls people either see or hear balls flying in parabolas. In the following, we will refer to stimulus orientation as the orientation of the parabola that is either horizontally or vertically oriented (see Figure 2). Whether an acoustically moving ball produces different temporal and spatial errors depending on its orientation on a touch screen that requires participants to determine when the ball will touch a ground line is unknown and was tested in the present experiments.

Likewise, for pitch it is known that it is a unitary attribute of auditory experience and that the cochlea of the inner ear performs the frequency analysis of sound (Licklider, 1951). Further, pitch influences sound localization processes (Kawashima & Sato, 2012; Mondor, Hurlburt, & Thorne, 2003) and thus impacts perceptual judgments (Bendor & Wang, 2005; Fadel et al., 2018). For instance, there is evidence that pitch is associated with height on the *y* axis (Walker, 1987) and does change movement parameters such as speed and amplitude (Küssner et al., 2014). We therefore assume that mean pitch alters perceptual judgments and interception movement behavior based on the following reasoning. Given that (i) pitch influences localization performance (Kawashima & Sato, 2012; Mondor, Hurlburt, & Thorne, 2003), (ii) different frequency bands impact time-to-arrival estimation (Gordon et al., 2013), and (iii) pitch does change movement parameters such as speed and amplitude (Küssner et al., 2014), it is reasonable to assume a direct effect of mean pitch on interception movements.

As argued above empirical evidence of how people intercept moving balls that are not visible is limited, finding an answer to this question requires a task in which it is possible to manipulate sound attributes, as one can do in a virtual moving ball task. Further the task needs to differentiate temporal and spatial errors in interception performance such as when and where the ball was perceived to touch the ground. Because most of the above-referenced evidence either did not manipulate sound attributes or investigate interception performance (e.g., Weger et al., 2016), it is an open empirical question whether, given the sensitivity of auditory perception to temporal information, the manipulation of sound attributes indeed impacts temporal errors more than spatial errors even though orientation of the parabola and pitch contain spatial features as well.

To this end, in the current study we tested whether manipulations of auditory stimuli would impact temporal more than spatial precision and accuracy given the higher sensitivity of the auditory system for processing temporal information. We explored whether pitch manipulations (Experiments 1 and 2) would impact temporal precision and accuracy more than spatial precision and accuracy. Furthermore, we tested whether stimuli presented in horizontal (Experiment 1) and vertical (Experiment 2) oriented parabolas would differently impact temporal precision and spatial precision (Grantham et al., 2003). We explored whether pitch manipulation will produce more temporal and spatial errors in vertical than horizontal oriented parabolas extending research that focused on horizontally oriented sounds (Neuhoff, 2016).

Experiment 1

To test the aforementioned hypotheses, in Experiment 1 participants were presented with sounds which moved along horizontal oriented parabolas (see Figure 2). Using a within-subject design, participants were confronted with five different pitches and asked to touch the screen to intercept, that is, judge where and when the stimulus would cross a visible line.

Method

Participants

Forty-four participants (25 female students, 19 male students; $M_{\text{age}} = 26.4$ years, $SD = 9.2$; 42 right handed, 2 left handed) took part in Experiment 1. The sample size was chosen on the basis of an a priori power analysis for a multivariate analysis of variance (MANOVA; within-factors effects), using G*Power 3.1 (Faul et al., 2009) with an estimated effect size of $f = .18$ (small effect of $\eta^2 = .03$), alpha = .05, a high power of 0.8, and a correlation among repeated measures of $r = .5$. Note that this effect size initially was considered because we aimed to implement a MANOVA test, but because normal distribution was violated for the dependent variables under consideration, a linear mixed model was performed instead. The participants signed informed consent prior to the beginning of the experiment and completed a questionnaire concerning handedness, age, and familiarity with touch screens and surround systems, the latter to assess potential familiarity with the experimental setup, such as time spent using a touch screen ($M = 3.3$ hr/day, $SD = 2.1$), playing electronic games ($M = 0.5$ hr/day, $SD = 0.3$), playing electronic games on a touch screen ($M = 0.4$ hr/day, $SD = 0.2$), using headphones ($M = 1.9$ hr/day, $SD = 1.4$), and using surround sound systems ($M = 1.9$ hr/day, $SD = 0.8$). In addition, participants were asked about their weekly fitness regimen; they reported being involved in sport or exercise activities for about 6.9 hr/day ($SD = 4.3$). The study was approved by the local ethics committee.

Inclusion criteria included normal hearing ability—the participants' perceived tones threshold (tested by Labor Cotral, Germany) varied at each frequency as follows: 500 Hz: $M = 41.1$ dB, $SD = 17.8$, 1000 Hz: $M = 28.8$ dB, $SD = 6.4$, 2000 Hz: $M = 44.6$ dB, $SD = 9.6$, 4000 Hz: $M = 44$ dB, $SD = 12.3$, 8000 Hz: $M = 18.2$ dB, $SD = 12.4$—and no reported neurological injuries or disorders. Debriefing and remuneration (7 €) was provided after the end of the experiment.

Materials and Experimental Design

We used a 43-inch touch screen (iiyama PROLITE TF4338MSC-B1AG, resolution 1920 × 1080, 60 Hz, 2.1 megapixels, full HD, multi-touch monitor, South Korea) to present the task and measure participants' manual interception behavior (Figure 1). The touch screen was positioned in front of the participant at a distance of approximately 50 cm. Loudspeakers were synchronized via a broadcast sound card (CREATIVE, USA) with five channels, which corresponded to five loudspeakers (GENELEC, G One BM, Finland) mounted around the touch screen. The laboratory sound level was measured via phonometer (Trotec SL400, Germany), with a constant intensity of 55 dB.

The auditory manipulations, generated digitally via Matlab (Mathworks, USA), were based on the script provided by Archontis Politis (https://github.com/polarch/Vector-Base-Amplitude-Panning, VBAP) implementing the vector-based amplitude panning method (Pulkki, 1997). The VBAP is designed to simulate motion in the auditory stimuli. In other words, due to multi-speaker-panning participants have the impression that audible sine-tone sound was programmed to be moving along a parabola on the touch screen's surface. More specifically, the VBAP allows to produce the auditory perception of a moving virtual sound source at any location on a hemisphere between the included loudspeakers by adjusting the amplitude for each loudspeaker separately. As the five loudspeakers were mounted around the screen, the sound can be produced at certain locations on the screen. At the beginning of each trial a white ground line (0.98 cm width × 94 cm length) and a start button were shown on a black screen. A white circle (4.9 cm diameter) representing a ball and the line appeared immediately after the button was pressed and the start button disappeared. The ball disappeared 500 ms later and at the same time the sound was started. Participants had to touch the screen to indicate when (temporal precision and accuracy) and where (spatial precision and accuracy) the auditory stimulus would land on the ground line, using the index finger of their dominant hand. After the end of each trial the start button appeared again indicating at which point the next trial could start. Before the beginning of the main experiment participants performed one block of 12 familiarization trials, hearing the auditory stimuli at 300, 600, and 1000 Hz, without any occlusion time at the final part of the stimulus. After these familiarization trials two blocks of 24 practical trials were performed using the same stimuli as before, but now with an occlusion time of 600 ms or 900 ms at the final part of the stimulus. The occlusion time was manipulated using the Audacity software (version 2.4.2, USA). Note that the manipulation used in these blocks was similar to that of the main experiment, but with different values of pitch, velocity, and occlusion time.

Performance feedback, consisting of the calculated numerical score of temporal and spatial errors, was presented after the end of each trial in the pretests (familiarization and practice trials) before the main experiment. Participants' relative performance on the pretests was calculated only for motivational reasons and was not included in the analysis. In the main experiment the percentage score of successful hits was presented after each bock of 45 trials. A correct hit was counted if the finger had touched the screen at a distance of maximum 350 pixels (17.15 cm) from the actual position of the middle point of the ball.

The main experiment had six blocks of 45 trials each; stimulus presentation was randomly generated for all trials. The experiment was implemented using Psychopy (version 3.7.2, USA). Our main manipulation is pitch of sounds. To identify the sensitivity to our auditory manipulations, a pilot test used different pitches in an identical protocol to that described above. The results of the pilot test corroborated the decision to use the following five pitches (100, 200, 400, 800, and 1200 Hz), which are within the human auditory range (Getzmann & Lewald, 2007; Gordon et al., 2013). The starting time of the auditory stimulus onset was constant (500 ms).

In addition to pitch manipulations we varied the ball trajectories as well in dimensions that require the participants in each trial to produce different landing positions of the ball and thus require interception behavior avoiding routine movements (Benguigui et al., 2003). We used three different trajectories on parabolas (in screen-related pixel space of $-0.01x^2 + 600$; $-0.005x^2 + 550$; $- 0.0025x^2 + 500$) with three durations of the stimuli (4.5 s, 6 s or 9 s) which produces 9 different constant velocities (i.e., constant in horizontal direction in Exp. 1 and in vertical direction in Exp. 2) of virtual ball flights. In addition, the starting point of the trajectory (left or right) and the auditory occlusion of stimulus (300, 700, or 1100 ms before hitting the ground) was varied (see Figure 2a).

Procedure

The participant was seated approximately 50 cm in front of a touch screen mounted vertically on a wall, surrounded by five loudspeakers; see Figure 1. The task always began after the participant pressed the start button and restarted after the participant's response about where and when the stimulus would land on the line; see Figure 2a. The experimental procedure lasted about 1 hr.

Insert Figures 1 and 2 about here

Statistical Analysis

The participant's accuracy was calculated by the mean (constant error) and precision was calculated by the standard deviation (variable error) of temporal and spatial errors. Note that the constant errors considered all means of the participants, thus mean of all means, while the variable errors considered the SD of the participants, thus mean of all SDs. The temporal difference score was calculated by subtracting the actual flight time from the time at which the participant touched the screen. The spatial difference score was calculated by subtracting the xcoordinate of the actual landing position from the one where the participant touched the screen. A negative value indicates that the participant touched the screen surface early (time)/ before (space) the auditory stimulus hit the ground line, and a positive value means the participant touched the screen surface later (time)/after (space) the auditory stimulus hit the ground line. More precisely, this calculation assessed temporal and spatial "*x*" errors. We use the term "lateral position" to indicate when a horizontally oriented spatial error was made (Experiment 1).

An additional calculation was done to assess "radial spatial" error, that is, the Euclidean distance between participant finger position on the touch screen and the stimulus landing position. Note that due to the fact that Euclidean calculation square the values only positive values can be presented. This additional calculation allowed us also to assess whether participants might also have touched the screen above or below the stimulus location, albeit they were instructed to touch the horizontal line. In other words, because stimuli moving in a parabola contain horizontal and vertical information, we measured participants' possible behavior in all coordinates.

Multilevel Analysis.

We employed linear mixed models (LMMs) to account for the effect of auditory stimuli (pitch of 100, 200, 400, 800, 1200 Hz) on the dependent variables, i.e. temporal, lateral position, and radial spatial errors using a self-developed R code (R Core Team, 2016).

A programmed artefact rejection calculation was performed to detect outliers at all data points of Experiments 1 and 2. The exclusion criterion considered values more than 1.5 times interquartile range above the 75%-quantile or below the 25%-quartile considering each participant separately. Based on this procedure for no dependent variable more than 5% of the data were excluded.

Results

Constant Errors (Accuracy)

We used the Shapiro–Wilk test to assess data distribution. This analysis showed that constant errors were not normally distributed: $W = .87, p < .0001$ for temporal, $W = .96, p < .0001$ for lateral position, and $W = .91, p < .0001$ for radial spatial. With respect to the effect of auditory manipulation on participants' accuracy, there was an effect on lateral position error, $\chi^2(4) = 61.52, p < .0001$, and a significant effect on radial spatial error, $\chi^2(4) = 12.26, p < .01$; but no effect of pitch on temporal error, $\chi^2(4) = 3.28, p = .51$.

According to Tukey Post hoc test no statistically significant difference was found for temporal constant errors (all *ps > .05*), but a significant difference were found for lateral position constant errors; between 100Hz x 200Hz, $z = 4.52, p < .001$, 100Hz x 400Hz, $z = 4.26, p < .001$, 800Hz x 200Hz, $z = -6.50, p < .001$, 200Hz x 1200Hz, $z = -5.56, p < .001$, 400Hz x 800Hz, $z = -6.19, p < .001$, 400Hz x 1200Hz, $z = -5.26, p < .001$, and radial spatial constant errors; between 800Hz x 200Hz, $z = -3.10, p < .01$. No statistically significant difference was found between the other possible task conditions, see Figures 3a and 4a.

Variable Errors (Precision)

We used the Shapiro–Wilk test to assess data distribution. This analysis showed that temporal error, $W = .50, p < .0001$ and lateral position error, $W = .98, p = .05$ were not normally distributed; but radial spatial was $W = .99, p = .30$. With respect to the effect of the pitch manipulation, no significant effect was present for temporal error, $\chi^2(4) = 4.19, p = .37$, for lateral position error, $\chi^2(4) = 7.14, p > .12$, but for radial spatial error, $\chi^2(4) = 15.03, p < .01$.

According to Tukey Post hoc test no statistically significant difference was found for temporal and lateral position variable errors (all *ps > .05*), but a significant difference was found for radial spatial variable errors; between 100Hz x 200Hz, $z = -3.62$, $p < .001$ and 800Hz x 200Hz, $z = -2.72$, $p < .05$. Indicating there were no effects of pitch manipulation on temporal, but on radial spatial variable errors; see Figures 3b, 4b, and 5b.

Insert Figures 3, 4 and 5 about here

Altogether the results of Experiment 1 suggested that some participant errors were consistently affected by the manipulation of pitch when participants intercepted moving balls. It is worth noting that the temporal constant and variable errors, as well as lateral position variable errors, were not affected by pitch manipulation, while lateral position constant and radial spatial constant and variable errors were.

Discussion

We predicted that auditory stimuli would impact temporal precision and accuracy more than spatial precision and accuracy. However, a more careful analysis of the results from Experiment 1 revealed that spatial accuracies (lateral position and radial spatial errors) and precision (radial spatial error) were affected by our pitch manipulation. How can we explain this? First, as argued above, pitch itself is related to perceptions of space (e.g., Weger et al., 2016). Second, as noted by Cai and Connell (2015) in a study in which they also presented auditory stimuli, the auditory domain can potentially impact both types of error, which they called tempo-spatial precision errors. Thus, although in our literature review we found auditory information to have a stronger impact on temporal errors, it is possible that pitch impacts spatial errors as well, but perhaps to a lesser degree.

As we argued in the Introduction, other stimulus dimensions, such as stimulus orientation, could have influenced our findings so we decided to conceptually replicate the experiment using a vertical orientation of the auditory stimulus. In our paradigm, the temporal reaction was mainly depending on perceiving the vertical location of the sound source at different time points: to anticipate when the ball will hit the ground line (height 0) the participant must know at which heights the ball is at certain time points. As vertical locations are more difficult to perceive or discriminate than horizontal locations (e.g. Weger et al., 2016), it might be possible that the temporal part of the task was too difficult which is why relatively high errors were present. Probably that is why we were not able to find any effect of pitch on the temporal errors. Participants were not able to temporally hit the target and that is why their performance could not be affected by pitch manipulations. If the parabola would be tilted 90°, the temporal response would depend on perceiving different horizontal locations, which was shown to be better than vertical sound localization in humans (e.g. Weger et al., 2016). Therefore, we would expect that the temporal response could be improved with a tilted parabola and effects of pitch might be revealed with this revised paradigm.

In sum, our data extend the findings of Weger et al.'s (2016) study using horizontally and vertically oriented stimuli from loudspeakers to our parabola stimuli, which contained both a horizontal and a vertical dimension. Given that our parabolas were oriented horizontally we cannot further specify how the vertical information may have been used compared to a condition in which parabolas would be vertically oriented. Therefore, a natural continuation of Experiment 1 was to test whether a vertically oriented parabola would affect interception performance and provide a more precise differentiation of temporal and spatial judgments

Experiment 2

Experiment 2 was identical to Experiment 1 with the exception that the parabolas were vertically oriented (see Figure 2b).

Method

Participants

Forty-five participants (21 female students, 24 male students, M_{age} = 24.9 years, *SD* = 8.6; 40 right handed, 5 left handed) who did not participate in Experiment 1 took part in Experiment 2. They signed informed consent prior to the beginning of the experiment and completed a questionnaire concerning handedness, age, and familiarity with touch screens and surround systems. Mean time spent using a touch screen was 2.9 hr/day (*SD* = 1.2), playing electronic games 0.6 hr/day (*SD* = 0.4), playing electronic games with a touch screen 0.4 hr/day (*SD* = 0.2), using headphones 2.0 hr/day (*SD* = 1.5), and using a surround sound system 2.6 hr/day (*SD* = 1.3). In addition, participants were asked about their weekly fitness; they reported participating in sports or exercise activities for about 7.4 hr/day (*SD* = 4.1). The study was approved by the local ethics committee. Participant inclusion criteria were the same as in Experiment 1.

Materials and Experimental Design

The materials for Experiment 2 were the same as for Experiment 1 with one difference: The touch screen was turned 90 degrees to the right, allowing us to display the parabolas in a vertical orientation moving top to bottom or bottom to top (see Fig. 2b). Note that we use the term “vertical position” to indicate that the spatial error was vertically oriented (Experiment 2).

Procedure

The procedure was identical to that in Experiment 1.

Results

Constant Error (Accuracy)

We used the Shapiro–Wilk test to assess data distribution. This analysis showed that constant errors were not normally distributed: $W = .85, p < .0001$ for temporal, $W = .98, p < .01$

for vertical position, and $W = .91$, $p = .0001$ for radial spatial. With respect to the effect of auditory manipulation on participants' accuracy, there was a significant effect of pitch on temporal error, $\chi^2(4) = 24.08$, $p < .001$, but no effect on vertical position error, $\chi^2(4) = 4.98$, $p = .28$, or radial spatial error, $\chi^2(4) = 6.14$, $p = .18$.

According to Tukey Post hoc test statistically significant differences were found for temporal constant errors between 400Hz x 200Hz, $z = -3.38$, $p < .01$, 100Hz x 800Hz, $z = -4.70$, $p < .001$, 200Hz x 800Hz, $z = -3.26$, $p < .01$. These results indicate an effect on temporal constant errors in almost all pitch conditions. No statistically significant effect was found for radial spatial error in any pitch condition. In addition, results for spatial constant errors are less systematic; see Figures 6a and 7a.

Variable Error (Precision)

We used the Shapiro–Wilk test to assess data distribution. This analysis showed that temporal variable error was not normally distributed: $W = .60$, $p < .001$, but vertical position, $W = .99$, $p = .79$, and radial spatial $W = .99$, $p = .17$ errors were. With respect to the effect of auditory manipulation on participants' precision, there was no significant effect of pitch on temporal error, $\chi^2(4) = 2.70$, $p = .60$, for vertical position error, $\chi^2(4) = 6.75$, $p = .14$, or radial spatial error, $\chi^2(4) = 3.21$, $p = .52$.

According to Tukey Post hoc test no statistically significant differences were found for temporal variables errors, vertical position variables errors; and for radial spatial variables errors (all *ps > .05*), see Figures 6b, 7b, and 8b.

Insert Figures 6, 7 and 8 about here

Results of Experiment 2 show that participants' temporal constant error was affected by pitch, when the parabolas were vertically oriented. On the other hand, the spatial and radial spatial constant and variable errors were not affected by the pitch manipulation.

Discussion

Experiment 2 aimed at extending and conceptually replicating the findings of Experiment 1, when using vertically orientated parabolas. The results of Experiment 2 corroborate the evidence found by Weger et al., (2016) as well as Butler and Humanski (1992) showing sensitivity to source location for auditory stimuli. Results suggest that temporal accuracy is impacted by pitch manipulation. For instance, at a high pitch of 800Hz temporal errors became larger and touches became earlier. A possible explanation for these results might be that when the stimuli are presented with a vertical orientation, participants are differently precise to make temporal and spatial judgments (Butler & Humanski, 1992; Weger et al., 2016).

Our findings, as hypothesized, suggest that manipulations of auditory stimuli affect temporal errors but do not affect spatial errors equally strong when parabolas are presented vertically. Alternative explanations will be discussed below. The present results extend evidence that pitch affects temporal errors in interceptive tasks when the auditory flight parabola is vertically oriented.

General Discussion

The present study aimed to test the hypothesis that manipulations of auditory pitch and orientation of auditory parabolas have a differential impact on temporal and spatial precision and accuracy in intercepting virtual moving balls. In general, our results show that the chosen auditory manipulations affected all three types of assessed accuracy and one precision, that is, temporal, spatial (lateral position and vertical position), and radial (spatial) errors. In Experiment

1, where parabolas were presented horizontally, pitch manipulations impacted lateral position and radial spatial accuracy as well as radial spatial precision, while in Experiment 2, where parabolas have been presented vertically, temporal accuracy was affected by pitch.

The combined findings of Experiments 1 and 2 are in line with those of other studies that tested the relation between different sound attributes and their effects on movement precision and accuracy (Küssner et al., 2014). A new finding is that different mean pitches was moderated by the orientation of the parabola, predominantly impacting spatial and radial spatial errors in Experiment 1 (i.e. with horizontal orientation) and temporal errors in Experiment 2 (i.e. with vertical orientation). We confirm that previous arguments about the sensitivity of the auditory system for vertical moving sounds and extend studies from perceptual judgments (Weger et al., 2016) that temporal precise responses can be well prepared in vertical moving sounds. In both experiments the relationship between pitch and error was not unidirectional and thus we argue that in the future parametric designs are needed to systematically whether linear or non-linear regressions can explain more variance.

Extending previous findings, we manipulated the auditory stimulus orientation and thus add to the understanding that pitch corresponds to fine motor accuracy, which is important, for instance, when playing music or intercepting balls. In addition, this finding agrees with physiological evidence indicating how the somatosensory cortex integrates perceptions of sound and movement production, as needed in precise interceptive tasks when vision is absent (Zelic et al., 2015).

Explaining the findings of our study from a motor control perspective is necessary. Our findings may also speak to the integration of auditory information in motor control theories (e.g. Wolpert et al., 1995). For instance, it seems that feedforward models (Wolpert et al., 1995) can successfully integrate and rely on auditory information if visual information is absent to guide motor interception. Albeit the functioning of the sensorimotor system was mainly challenged to predict ball landing time and position, the present study adds to the discussion of the how humans rely on other sensory systems when vision is not abundant. Overall, walkers recognize their own sound of landing during hurdling run, more interesting is that they adapt to manipulated sound of landing very well after training (Kennel et al., 2014). The so called acoustic reafference training has been proposed to test where athletes during their movements rely on sound and improve their motor performance (Pizzera et al., 2017). In short, auditory information is used by the motor system that is highly sensitive to create internal models to predict and interact with the environment (Wolpert et al., 1995).

Whether the early visual display of the ball has an impact to the perception of the auditory information and the interception behavior may be a task for inter-modality research in the future. For instance, a study by Rinaldi et al. (2016) showed that auditory pitch also influenced size processing such that high-pitched sounds were perceptually associated with smaller visual stimuli. We do not know in our study whether the imagined size of the displayed ball when combined with high or low pitches would be perceived differently and thus systematically influence judgments of when the ball would cross the ground line. However, if this were the case, we would assume that this would produce only systematic constant errors, in contrast to our findings.

Applied interventions for blind people may profit from our results. In fact, the use of auditory stimuli in complex games as Goal ball has been reported to affect players body language (Gomes-da-Silva, Almeida & Antério, 2015). It is argued that the practice of Goal ball in team builds a collective aim, therefore participants may synchronize their movements with teammates through auditory information. Another important application for the future would be the clinical context; for instance, addressing the question how acoustic information can help people with Parkinson's Disease in interception tasks (Bieńkiewicz et al., 2014).

Further research is needed to scrutinize exactly how temporal and spatial precision and accuracy are affected by other types of sound attributes and their interaction effects within one modality or in multimodality scenarios. Another limitation of our study is that our paradigm did not control for potential top-down regulation of perceptual judgments. For instance, we do not know if the fact that participants filled out the questionnaire concerning handedness, age, and familiarity with touch screens and surround systems before the task produced potential biases in how they performed the task. This, however, would have been equally biasing for all participants and would not explain the differential effects we found for sound attributes and their manipulations.

In summary, we decided to manipulate two important sound attributes with pitch and stimulus orientation and extended the findings from previous studies to intercepting virtual balls flying in parabolas. We controlled and kept other sound attributes constant, but it is evident that, for instance, loudness and other attributes might affect the generalization of our findings in an interception task. In addition, the pitch manipulation in itself promotes effects other than those we studied in regard to the motor system.

We conclude that this new empirical evidence adds to the theoretical debate on how temporal and spatial precision errors are distinctly affected by auditory manipulations (Loeffler et al., 2018). Together, the two experiments presented in this study contribute to the understanding of temporal and spatial precision and accuracy in interceptive tasks when visual information is not reliable or sufficient about the to-be-intercepted object. We argue that auditory stimulus orientation particularly affects precision when intercepting acoustically perceived, virtually moving balls. Highlighting the importance of auditory information and how people use it is certainly a sound way to understand how humans interact with the environment.

Conflict of interest

In accordance with Taylor & Francis policy and my ethical obligation as a researcher, I am reporting that I receive funding from DFG (The project was supported by the German Research Foundation (DFG) with two grants awarded to Markus Raab (RA 940/15-2) and Rouwen Cañal-Bruland (CA 635/2-2). I have disclosed those interests fully to Taylor & Francis, and I have in place an approved plan for managing any potential conflicts arising from that involvement.

References

Altieri, N., Stevenson, R. A., Wallace, M. T., & Wenger, M. J. (2015). Learning to associate auditory and visual stimuli: Behavioral and neural mechanisms. *Brain Topography*, *28*(3), 479–493. https://doi.org/10.1007/s10548-013-0333-7

Bendor, D., & Wang, X. (2005). The neuronal representation of pitch in primate auditory cortex. *Nature*, *436*(7054):1161–1165. https://doi.org/10.1038/nature03867

Benguigui, N., Ripoll, H., & Broderick, M. P. (2003). Time-to-contact estimation of accelerated stimuli is based on first-order information. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(6), 1083–1101. https://doi.org/10.1037/0096-1523.29.6.1083

Bieńkiewicz, M., Young, W. & Craig, C. (2014). Balls to the wall: How acoustic information from a ball in motion guides interceptive movement in people with Parkinson's disease. *Neuroscience, 275*, 508–518.

Brenner, E., Cañal-Bruland, R., & van Beers, R. J. (2013). How the required precision influences the way we intercept a moving object. *Experimental Brain Research*, *230*(2), 207–218. https://doi.org/10.1007/s00221-013-3645-7

Butler R. A., & Humanski R. A. (1992). Localization of sound in the vertical plane with and without high frequency spectral cues. *Perception & Psychophysics 51*(2), 182–186. https://doi.org/10.3758/bf03212242

Cai, Z. G., & Connell, L. (2015). Space–time interdependence: Evidence against asymmetric mapping between time and space. *Cognition*, *136*, 268–281. https://doi.org/10.1016/j.cognition.2014.11.039

Cañal-Bruland, R., Müller, F., Lach, B., & Spence, C. (2018). Auditory contributions to visual anticipation in tennis. *Psychology of Sport and Exercise, 36*, 100–103. https://doi.org/10.1016/j.psychsport.2018.02.001

Fadel, C. B. X., Ribas, A., Lüders, D., Fonseca, V. R., & Cat, M. N. L. (2018). Pitch-matching accuracy and temporal auditory processing. *International Archives of Otorhinolaryngology*, *22*(2), 113–118. https://doi.org/10.1055/s-0037-1603763

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G* Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, *41*(4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149

Getzmann, S., & Lewald, J. (2007). Localization of moving sound. *Perception & Psychophysics*, *69*(6), 1022–1034. https://doi.org/10.3758/bf03193940

Gomes-da-Silva, P., Almeida, J., & Antério, D. (2015). A comunicação corporal no jogo de Goalball. *Movimento (ESEFID/UFRGS), 21*(1), 25-40. doi: https://doi.org/10.22456/1982-8918.43323

Gordon, M. S., Russo, F. A., & MacDonald, E. (2013). Spectral information for detection of acoustic time to arrival. *Attention, Perception, & Psychophysics*, *75*(4), 738–750. https://doi.org/10.3758/s13414-013-0424-2

Grantham, D. W., Hornsby, B. W. Y., & Erpenbeck, E. A. (2003). Auditory spatial resolution in horizontal, vertical, and diagonal planes. *The Journal of the Acoustical Society of America, 114*(2), 1009-1022. https://doi.org/10.1121/1.1590970

Gray, R. (2009). How do batters use visual, auditory, and tactile information about the success of a baseball swing? *Research Quarterly for Exercise and Sport*, *80*(3), 491–501. https://doi.org/10.1080/02701367.2009.10599587

Kawashima, T., & Sato T. (2012). Adaptation in sound localization processing induced by interaural time difference in amplitude envelope at high frequencies. *PLOS ONE*, 7(7), Article e41328. https://doi.org/10.1371/journal.pone.0041328

Kennel, C., Hohmann, T., & Raab M. (2014). Action perception via auditory information: Agent identification and discrimination with complex movement sounds. *Journal of Cognitive Psychology*, 26 (2), 157-165, doi: 10.1080/20445911.2013.869226

Kom Komeilipoor, N., Rodger, M., Cesari, P. & Craig, C. (2015). Movement and perceptual strategies to intercept virtual sound sources. *Frontiers in Neuroscience, 9*, 149, https://doi.org/10.3389/fnins.2015.00149

Küssner M. B., Tidhar D., Prior H. M., & Leech-Wilkinson, D. (2014). Musicians are more consistent: Gestural cross-modal mappings of pitch, loudness and tempo in real-time. *Frontiers in Psychology*, *5*, 789. https://doi.org/10.3389/fpsyg.2014.00789

Licklider, J.C.R. (1951). A duplex theory of pitch perception. *The Journal of the Acoustical Society of America*, *23*(1), 147-147. https://doi.org/10.1121/1.1917296

Loeffler, J., Cañal-Bruland, R., Schroeger, A., Tolentino-Castro, J. W., & Raab, M. (2018). Interrelations between temporal and spatial cognition: The role of modality-specific processing. *Frontiers in Psychology*, *9*, 2609. https://doi.org/10.3389/fpsyg.2018.02609

López-Moliner, J., Brenner, E., Louw, S., & Smeets, J. B. J. (2010). Catching a gently thrown ball. *Experimental Brain Research*, *206*(4), 409–417. https://doi.org/10.1007/s00221-010-2421-1

Mondor, T. A., Hurlburt, J., & Thorne, L. (2003). Categorizing sounds by pitch: Effects of stimulus similarity and response repetition. *Perception & Psychophysics, 65*(1), 107–114. https://doi.org/10.3758/BF03194787

Müller, F., Jauernig, L. & Cañal-Bruland, R. (2019). The sound of speed: How grunting affects opponents’ anticipation in tennis. *PLOS ONE, 14*(4): e0214819.

Neuhoff, J. G. (2016). Looming sounds are perceived as faster than receding sounds. *Cognitive Research: Principles and Implications*, *1*, Article 15. https://doi.org/10.1186/s41235-016-0017-4

O'Brien, B., Juhas, B., Bieńkiewicz, M., Pruvost, L., Buloup, F., Bringnoux, L., & Bourdin, C. (2020). Online sonification for golf putting gesture: Reduced variability of motor behaviour and perceptual judgement. *Experimental Brain Research*, *238*(2), 883–895. https://doi.org/10.1007/s00221-020-05757-3

O’Connor, N., & Hermelin, B. (1972). Seeing and hearing and space and time. *Perception & Psychophysics*, *11*(1), 46–48. https://doi.org/10.3758/BF03212682

Ondobaka, S., Kilner, J., & Friston, K. (2017). The role of interoceptive inference in theory of mind. *Brain and Cognition*, *112*, 64–68. https://doi.org/10.1016/j.bandc.2015.08.002

Onishi, T., Yasuda, K., Kawata, S., & Iwata, H. (2018). Development of a rhythmic auditory biofeedback system to assist improving the kinetic chain for bat swing performance. *ROBOMECH Journal*, *5*, Article 12. https://doi.org/10.1186/s40648-018-0107-9

Pizzera, A., Hohmann, T., Streese, L., Habbig, A., & Raab, M. (2017). Long-term effects of acoustic reafference training (ART). *European journal of sport science*, *17*(10), 1279–1288. https://doi.org/10.1080/17461391.2017.1381767

Pulkki, V. (1997). Virtual sound source positioning using vector base amplitude panning. *Journal of the Audio Engineering Society*, *45*(6), 456–466.

R Core Team (2016) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Recanzone, G. H. (2009). Interactions of auditory and visual stimuli in space and time. *Hearing Research*, *258*(1-2), 89–99. https://doi.org/10.1016/j.heares.2009.04.009

Rinaldi, L., Lega, C., Cattaneo, Z., Girelli, L., & Bernardi, N. F. (2016). Grasping the sound: Auditory pitch influences size processing in motor planning. *Journal of Experimental Psychology: Human Perception and Performance*, *42*(1), 11–22. https://doi.org/10.1037/xhp0000120

Rosenblum, L. D., Carello, C. & Pastorre, R. E. (1987). Relative effectiveness of three stimulus variables for locating a moving sound source. *Perception, 16*, 175-186. https://doi.org/10.1068/p160175

Savelsbergh, G. J. P., Whiting, H. T. A., Pijpers, J. R., & van Santvoord, A. A. M. (1993). The visual guidance of catching. *Experimental Brain Research*, *93*, 148–156. https://doi.org/10.1007/BF00227789

Sors, F., Murgia, M., Santoro, I., Prpic, V., Galmonte, A., & Agostini, T. (2017). The contribution of early auditory and visual information to the discrimination of shot power in ball sports. *Psychology of Sport and Exercise*, *31*, 44–51. https://doi.org/10.1016/j.psychsport.2017.04.005

Susini, P., McAdams, S., & Winsberg, S. (1999). A multidimensional technique for sound quality assessment. *Acta Acustica United with Acustica*, 85, 650–656.

Takeuchi, T. (1993). Auditory information in playing tennis. *Perceptual and Motor* Skills, 76(3_suppl), 1323–1328. https://doi.org/10.2466/pms.1993.76.3c.1323

Vercillo, T., Tonelli, A. & Gori, M. (2017). Intercepting a sound without vision. *PLoS One, 12*, e0177407

Walker, R. (1987). The effects of culture, environment, age, and musical training on choices of visual metaphors for sound. *Perception Psychophysics*, *42*, 491–502. https://doi.org/10.3758/BF03209757

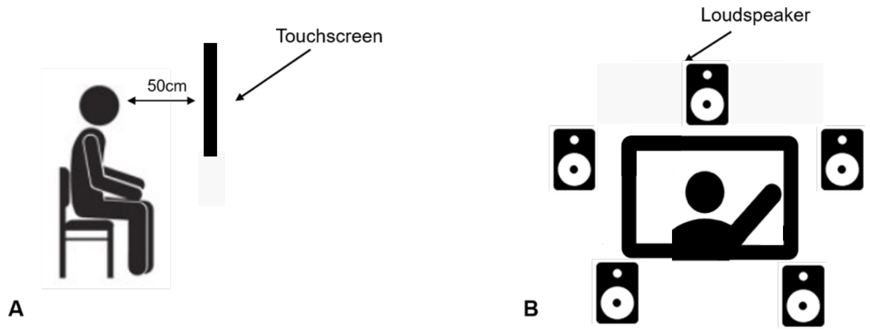
Wolpert, D. M., Ghahramani, Z. & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science, 29*, 269(5232), 1880-2. https://doi: 10.1126/science.7569931

Weger, M., Marentakis, G., & Höldrich R. (2016). Auditory perception of spatial extent in horizontal and vertical plane. In *Proceedings of the 19th International Conference on Digital Audio Effects* (pp. 301–308). Brno University of Technology.

Zelic, G., Kim, J., & Davis, C. (2015). Articulatory constraints on spontaneous entrainment between speech and manual gesture. *Human Movement Science*, *42*, 232–245. https://doi.org/10.1016/j.humov.2015.05.009

Figure 1

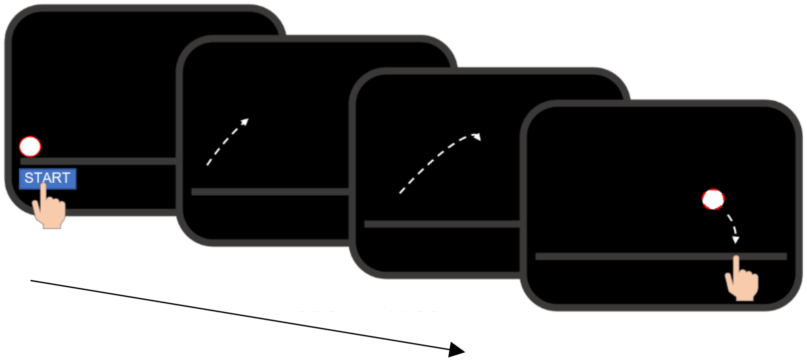
Overview of the Experimental Setup



Note. Panel A: Lateral view: The participant was seated approximately 50 cm in front of a touchscreen mounted vertically on a wall. Panel B: Front view: The loudspeakers were positioned around the touch screen. All loudspeakers had the same distance to the participant's head (ears).

Figure 2a

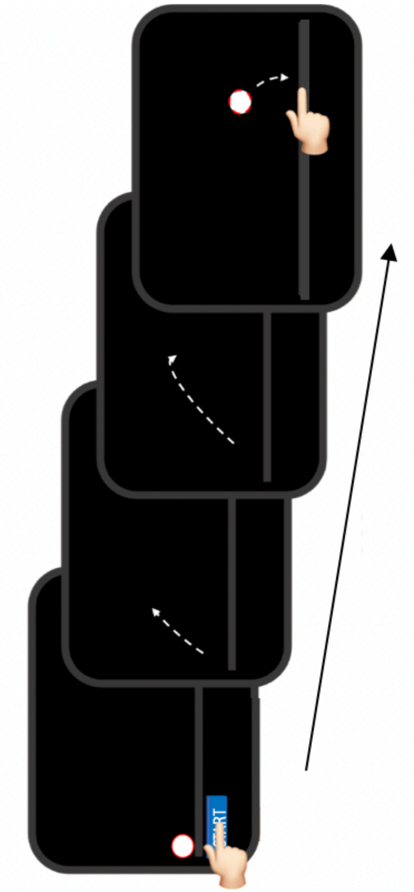
Experimental Procedure Experiment 1



Note. After pressing the start button, the virtual auditory stimulus began, simulating a ball flying in a parabolic manner (inverted U-shape). Participants were asked to predict the location (spatial precision and accuracy were calculated) and the moment (temporal precision and accuracy were calculated) of the ball hitting the ground line. Note that the ball was not visually presented, but only the auditory stimuli.

Figure 2b

Experimental Procedure Experiment 2



Note. After pressing the start button, the virtual auditory stimulus began, simulating a ball flying in a parabolic manner (C-shape). Participants were asked to predict the location (spatial precision and accuracy were calculated) and the moment (temporal precision and accuracy were calculated) of the ball hitting the ground line. Note that the ball was not visually presented, but only the auditory stimuli.

Figure 3a.

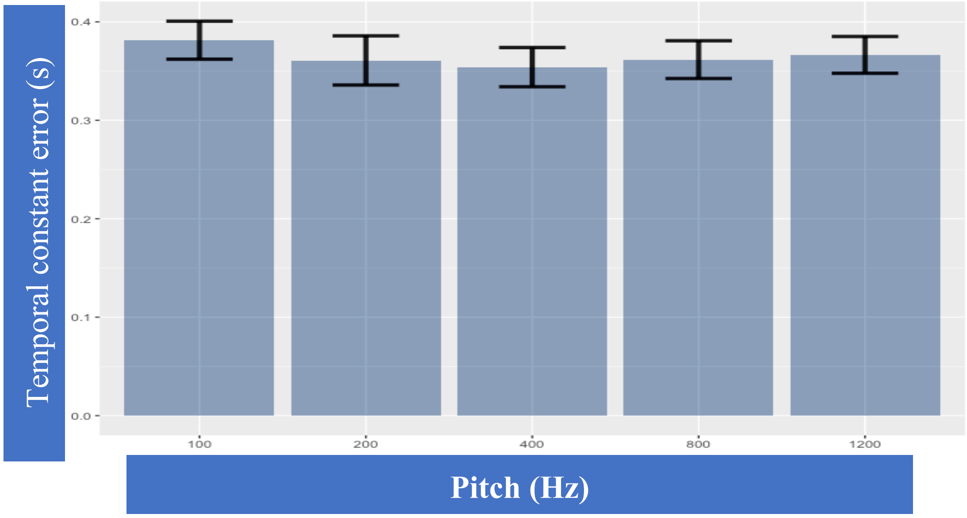


Figure 3b.

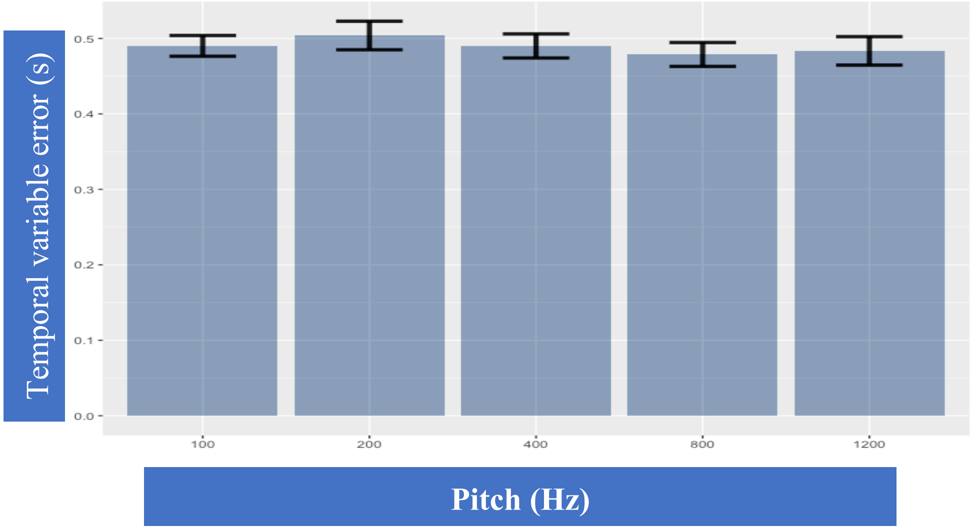


Figure 4a.

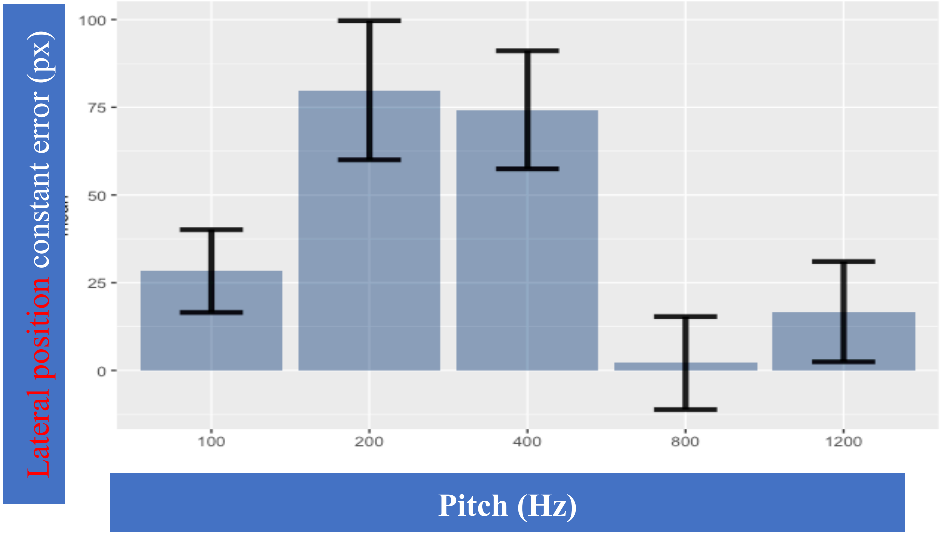


Figure 4b.

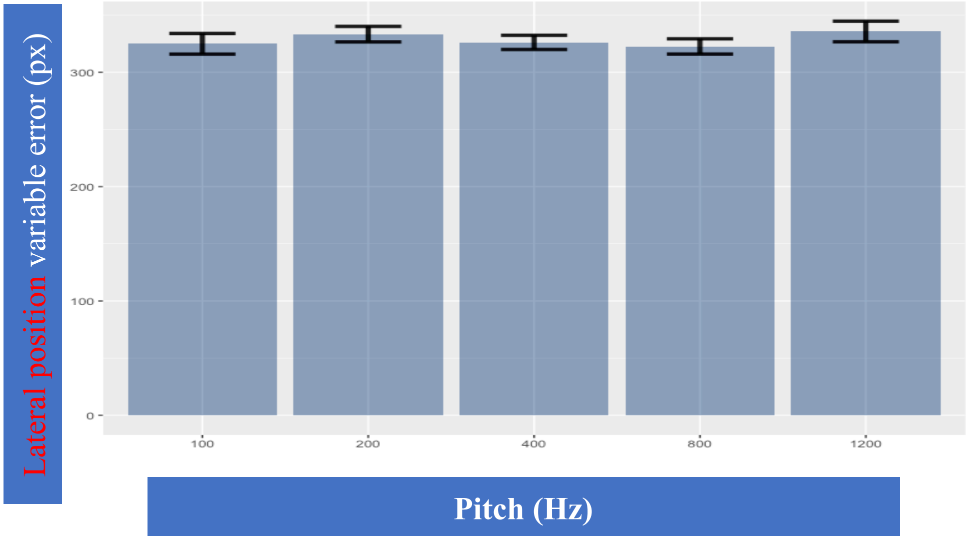


Figure 5a.

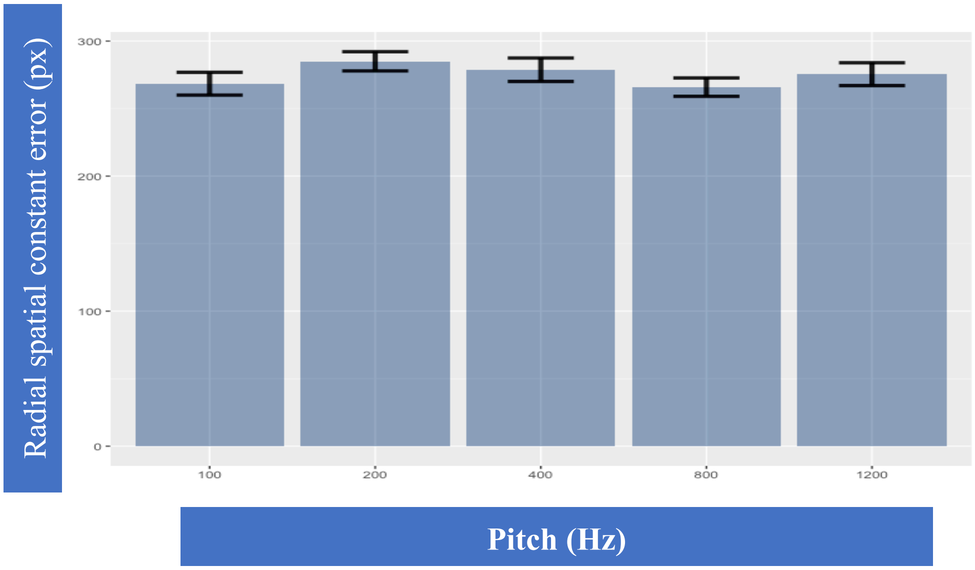


Figure 5b.

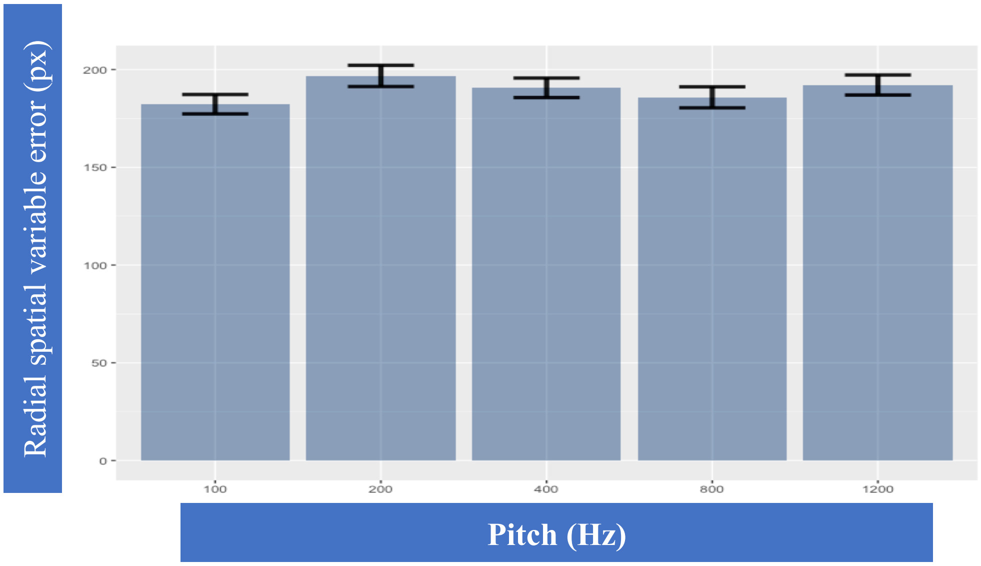


Figure 3a.

Temporal accuracy.

Participants' temporal constant error

Figure 3a. Results of the linear mixed model. The effect of Pitch on temporal constant error (mean and CI).

Figure 3b.

Temporal precision.

Participants' temporal variable error

Figure 3b. Results of the linear mixed model. The effect of Pitch on temporal variable error (mean and CI).

Figure 4a.

Spatial accuracy.

Participants' lateral position constant error.

Figure 4a. Results of the linear mixed model. The effect of Pitch on lateral position constant error (mean and CI).

Figure 4b.

Spatial precision.

Participants' lateral position variable error.

Figure 4b. Results of the linear mixed model. The effect of Pitch on lateral position variable error (mean and CI).

Figure 5a.

Radial spatial accuracy.

Participants' radial spatial constant error

Figure 5a. Results of the linear mixed model. The effect of Pitch on radial spatial constant error (mean and CI).

Figure 5b.

Radial spatial precision.

Participants' radial spatial variable error

Figure 5b. Results of the linear mixed model. The effect of Pitch on radial spatial variable error (mean and CI).

Figure 6a.

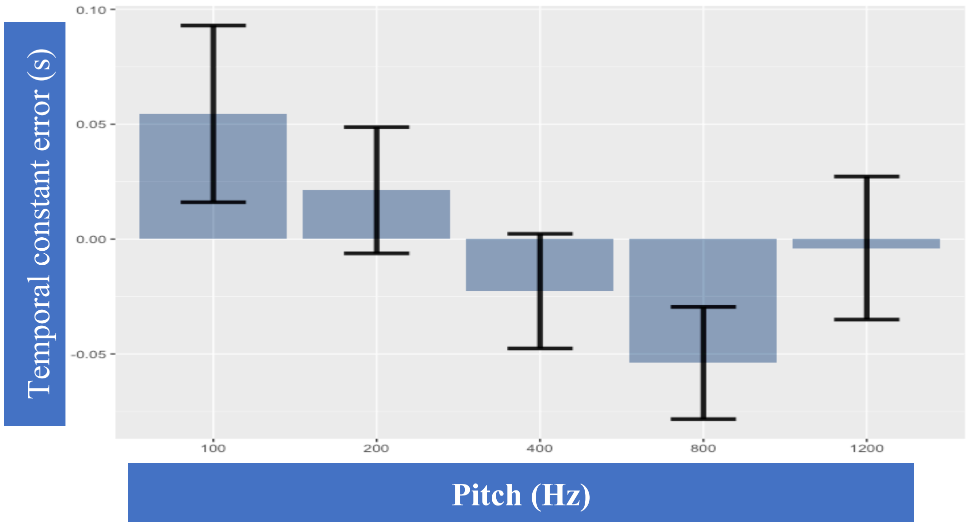


Figure 6b.

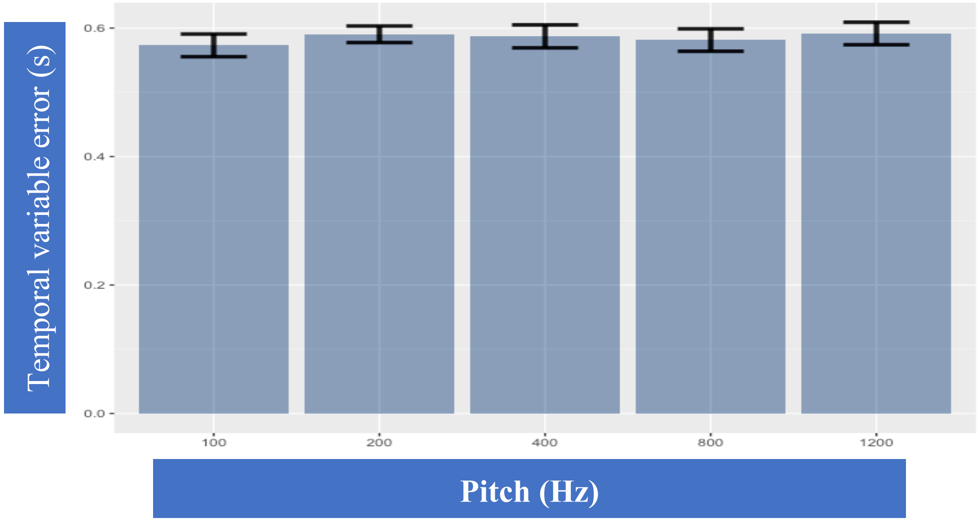


Figure 7a.

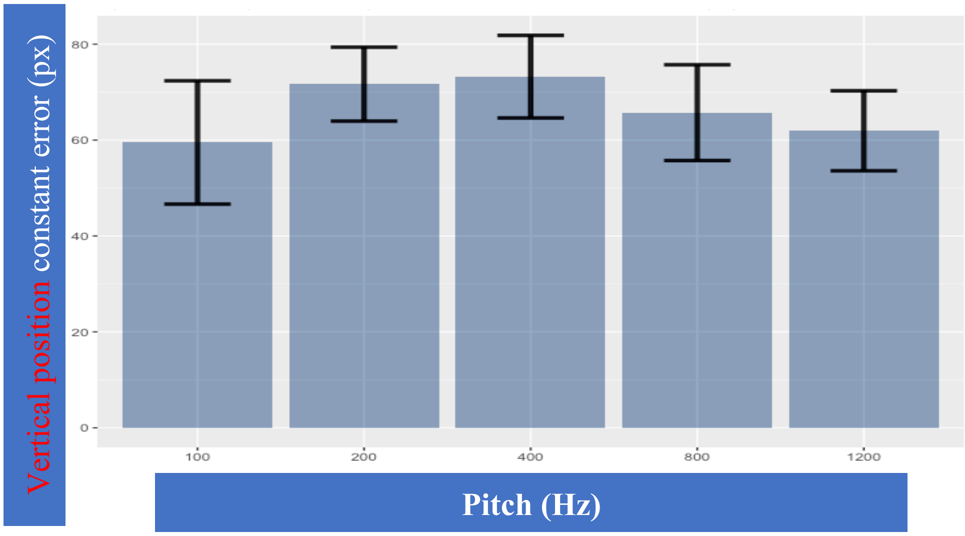
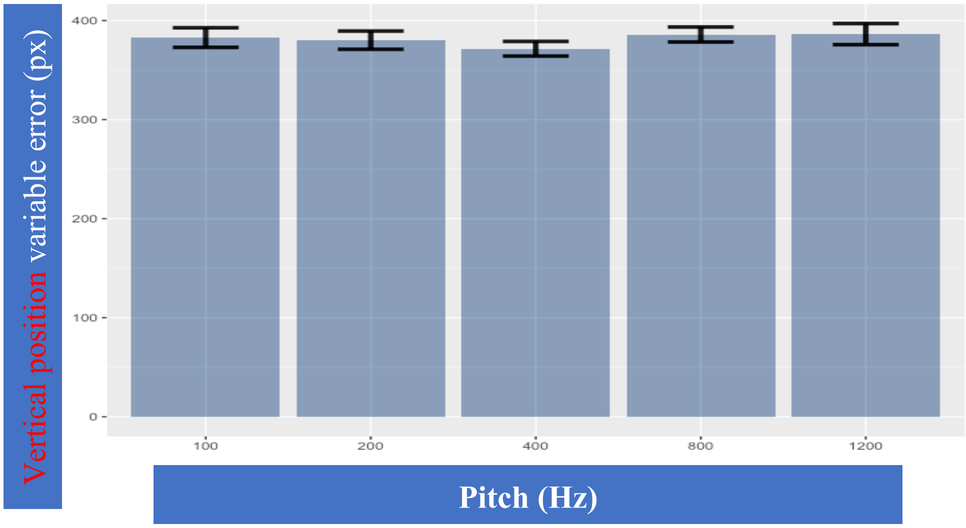


Figure 7b.



.

Figure 8a.

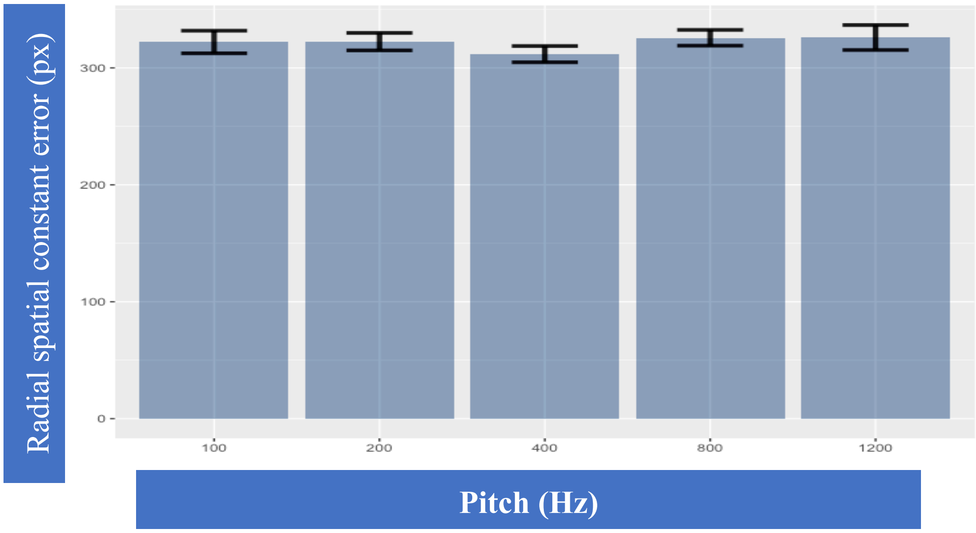


Figure 8b.

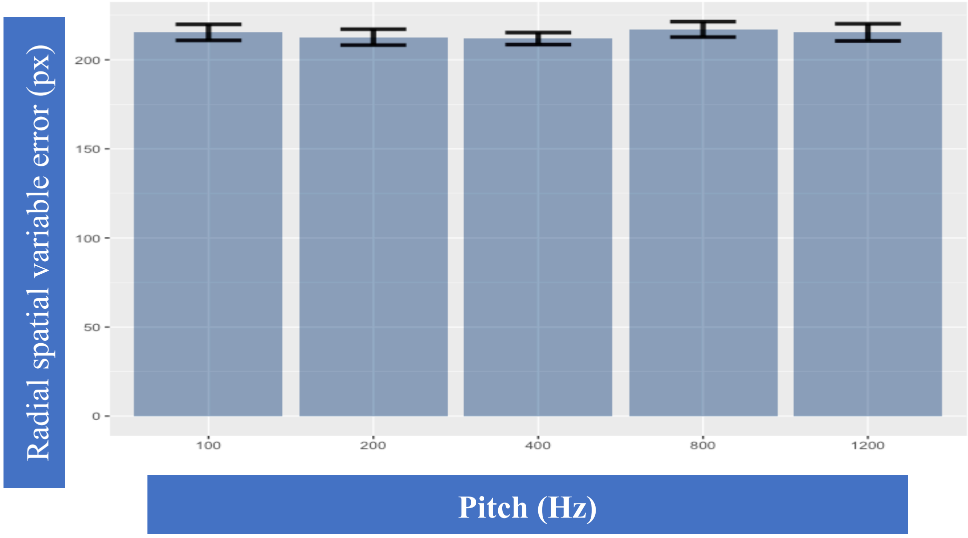


Figure 6a.

Temporal accuracy.

Participants' temporal constant error

Figure 6a. Results of the linear mixed model. The effect of Pitch on temporal constant error (mean and CI).

Figure 6b.

Temporal precision.

Participants' temporal variable error

Figure 6b. Results of the linear mixed model. The effect of Pitch on temporal variable error (mean and CI).

Figure 7a.

Spatial accuracy.

Participants' vertical position. constant error (mean and CI).

Figure 7a. Results of the linear mixed model. The effect of Pitch on vertical position constant error (mean and CI).

Figure 7b.

Spatial precision.

Participants' vertical position variable error (mean and CI).

Figure 7b. Results of the linear mixed model. The effect of Pitch on vertical position variable error variable error (mean and CI).

Figure 8a.

Radial spatial accuracy.

Participants' radial spatial constant error

Figure 8a. Results of the linear mixed model. The effect of Pitch on radial spatial constant error (mean and CI).

Figure 8b.

Radial spatial precision.

Participants' radial spatial variable error

Figure 8b. Results of the linear mixed model. The effect of Pitch on radial spatial variable error (mean and CI).