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Supplemental Information

Spatial Cues Influence Time Estimations in Deaf Individuals

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Supplemental Information

Participant	Age	Sex	**Age at deafness detection**	**Hearing aid use**	**Age at sign language first exposure**
S01	56	F	From birth	Uses currently	26 years old
S02	42	M	From birth	Uses currently	Unknown
S03	34	F	From birth	Uses currently	6 years old
S04	33	F	From birth	Uses currently	From birth
S05	23	F	From birth	Used in the past	From birth
S06	28	F	7 years old	Uses currently	18 years old
S07	24	F	From birth	Used in the past	15 years old
S08	37	F	5 years old	Uses currently	13 years old
S09	60	M	From birth	Used in the past	From birth
S10	21	F	13 years old	Never used	19 years old
S11	26	F	From birth	Used in the past	From birth
S12	29	M	3 years old	Used in the past	6 years old
S13	21	F	From birth	Uses currently	From birth
S14	37	F	From birth	Uses currently	3 years old
S15	73	M	6 years old	Never used	7 years old
S16	35	M	From birth	Used in the past	6 years old
S17	28	M	From birth	Uses currently	25 years old

Table S1. Demographic information about deaf participants obtained through self-report questionnaires, Related to Figure 1.

Transparent Methods

Participants

A group of 18 deaf participants (mean age±SEM: 35.7±3.5 yo; F=9) and 18 age and gender-matched hearing participants (32.4±1.5 yo; F=9; $t_{21.2}$= 0.86, p=0.4) took part in the study. Deaf participants were recruited at the National Association for Deaf (Ente Nazionale per la protezione e assistenza dei Sordi), in Genova, Italy. One deaf and one hearing participant were excluded from statistical analysis because they were identified as outliers (i.e. score in at least one task differing more than three standard deviations from the mean score of the group), giving rise to a final sample of 17 subjects per group. All participants reported no history of neurological or cognitive deficits, they had normal or corrected-to-normal vision and they were right-handed by self-report. All deaf participants had bilateral moderate to profound hearing loss, and did not receive a cochlear implant (see Table S1 for details). The research protocol was approved by the ethics committee of the local health service (Comitato Etico, ASL3 Genovese, Italy) and conducted in line with the Declaration of Helsinki. Written informed consent was obtained prior to testing.

Stimuli and procedure

Participants were sitting in front of an array of 23 light-emitting devices placed at a distance of 180 cm and spanning ±25° of visual angle (with 0° representing the central device, negative values on the left, and positive values on the right; Fig. 1, upper panels). Their body midline was aligned with the central device position. They performed three temporal bisection tasks, and one spatial bisection task as a control. The order of temporal and spatial blocks was counterbalanced across subjects. In each task, subjects see a sequence of three consecutive flashes (2.3° diameter, 75 ms duration) for a fixed trial duration of 1500 ms. For deaf participants, a hearing person fluent in Italian sign language was involved for instructions and questions. Before testing, participants were warned to maintain a stable head position straight ahead throughout testing. A short training session with feedbacks was conducted to make participants familiar with the task and to be sure they understood it correctly. They were informed from the beginning that the first flash was always produced by a device placed on their left, whereas the last flash by a device on their right. No feedbacks were given during experimental sessions. Procedure was similar to our previous paper investigating auditory spatial bisection abilities in blind participants (Gori et al., 2018).

Temporal Bisection Tasks

In temporal bisection tasks, participants judged verbally whether the second flash (S2) was temporally closer to the first flash (S1; -25°, -750ms considering 0ms the halfway point of the trial duration) or to the third flash (S3; +25°, +750 ms). S2 could occur randomly at an intermediate time point between -750ms (corresponding to the trial start time) and +750ms in time (corresponding to the trail end time), determined through the method of constant stimuli. To evaluate the role of spatial cues in time perception, spatial distances between the three flashes were manipulated to create three different temporal bisection tasks (Fig. 1, upper panels from left to right): *independent space*, *coherent space* and *opposite space* temporal bisection tasks, with spatial distances between visual stimuli which could be independent, coherent or opposite with respect to time intervals respectively. In the *independent space* temporal bisection, S2 was always delivered from 0° in space, which corresponded to the central light-emitting device. To correctly compute this task participant had to rely exclusively on temporal features since the spatial distance between S1-S2 was identical to the spatial distance between S2-S3, making spatial aspects entirely uninformative. Among temporal bisection tasks, the *independent space* one was always performed as the first one, with the order of the other two tasks randomly varying across participants. In the *coherent space* temporal bisection task, temporal intervals between S1-S2 and S2-S3 were directly proportional to spatial distances between the three flashes (e.g. a shorter temporal delay between S1-S2 was associated with a shorter spatial distance between the two flashes). The exact spatial position associated with each temporal delay of S2 is reported in the upper horizontal axis of the central psychometric function in Figure 1. Considering that the total trial duration was 1500ms and the number of speakers was 23, when S2 was for example presented at -682ms (i.e. with a delay of 68ms from S1) it was delivered from the second device on the left; when it was presented at -614ms (i.e. with a delay of 136ms from S1) it was delivered from the third speaker, and so on. In this condition, spatial cues could be used by subjects to infer temporal metric. Instead, in the *opposite space* temporal bisection task time intervals between the three lights were inversely proportional to space distances (e.g. a shorter temporal delay between S1-S2 was associated with a longer spatial distance between the two flashes), making space informative but in the opposite direction with respect to time. Again, the exact spatial position associated with each temporal delay of S2 is reported in the upper horizontal axis of the psychometric function on the right in Figure 1. In the *opposite space* temporal bisection task, S2 was delivered from the second speaker on the left when it was presented at +682ms (i.e. with a delay of 1432ms from S1), it was delivered from the third speaker on the left when it was played at +614ms (i.e.with a delay of 1364ms from S1), and so on.

Spatial Bisection Task

In the *spatial bisection task* (control experiment), participants were asked to verbally report whether S2 was closer to S1 or to S3 in the space domain. Differently to temporal bisection tasks, S2 occurred randomly at an intermediate position from -25° to +25° in space but it was always presented at 0ms (i.e. 750ms after S1, which corresponded to the middle time of the temporal sequence between S1-S3). As for the S2 position in the temporal bisection tasks, the spatial position of S2 in the spatial bisection task was determined using the method of constant stimuli.

Data analysis

For each task, we calculated the proportion of trials where the second flash was perceived as closer to the third flash and data were fitted by cumulative Gaussian functions. Following standard psychophysical procedure (Kingdom and Prins, 2010), PSE and threshold estimates were obtained from the mean and standard deviation of the best fitting function, and standard errors for the bisection PSE and threshold estimates were calculated by bootstrapping (Efron and Tibshirani, 1993). Specifically, we used a custom algorithm that has been previously validated in many published papers involving children (e.g. Gori et al., 2008) and clinical participants (e.g. Gori et al., 2014, Gori et al., 2018) whose performance was far from being optimal and similar deficits in bisection tasks were reported. The algorithm is based on Bootstrap technique; it automatically verifies the goodness of fit of the psychometric function and, when it is not significant, it assigns as threshold the worst value one subject can get (i.e. max threshold). In our case, two subjects were interpolated in the *opposite space* condition, and one subject was interpolated in the *independent space* condition. Moreover, some deaf participants based their answers in the *opposite space* temporal bisection task on spatial features (i.e. when space distances were incoherent with respect to time intervals), resulting in inverted psychometric functions with threshold expressed by negative values (values closer to 0 meaning good precision but in the spatial domain). In order to include these results together with those of deaf individuals who performed the *opposite space* task without inverting the psychometric function, we applied a conversion to negative thresholds as previously in Gori et al. 2018. Given thresholds (t) for the *opposite space* bisection task, negative values t_{neg} were converted to $t'_{neg} = t_{neg} - \min(t) + \max(t)$. This transformation allowed us to treat thresholds as a continuum, ranging from low thresholds representing good precision in the temporal domain to high thresholds representing poor temporal performance but good precision in the spatial domain.

To investigate temporal bisection precision, statistical comparisons between thresholds were performed with an omnibus two-way ANOVA, considering group (hearing, deaf) as a between-subjects factor, and task (*independent*, *coherent*, *opposite*) as a within-subjects factor. For each group, a follow-up one-way ANOVA was carried out with the task (*independent*, *coherent*, *opposite*) as a within-subjects factor. To control whether an early exposure to sign language was impacting on the performance, deaf participants were also split into early and late based on sign language first exposure (cut-off: three years old) and a permutation ANOVA with group (early, late) as a between-subjects factor, and task (*independent*, *coherent*, *opposite*) as a within-subjects factor was run. To perform this analysis, we applied the *aovp* function of the lmPerm package in R (Wheeler, 2010). For the spatial bisection task, thresholds were analyzed with a one-way ANOVA with group (hearing, deaf) as a between-subjects factor. For both bisection tasks, post-hoc comparisons were conducted with two-tailed t-tests, with probabilities treated as significant when lower than 0.05 after Bonferroni correction.

Moreover, for the group of deaf individuals Pearson correlational analyses were carried out to evaluate the relationship between the performance at the three conditions (*independent space*, *coherent space* and *opposite space*) of temporal bisection task and the performance at the spatial bisection task.

Data and Software Availability

Data and/or code used in the study are available from the corresponding author upon direct request.

Supplemental References

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