Article

Reinstatement of terminal event representations after context transfer

Published online: 20 November 2026

Open access

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capstract:2611.00039v1 [q-bio.NC] 20 Nov 2026

A terminal signal can be predicted from the physical apparatus that emits it or from the activity it brings to an end. We separated these sources of prediction by transferring an interrupted appliance run to a second display with an independently assigned acoustic signature. We trained frequency decoders on isolated sounds and evaluated them at silent terminal events in 72 participants at two recording sites. A decoder labeled by the originating display's signature yielded an area under the receiver operating characteristic curve of 0.62 after transfer and 0.50 after substitution (paired difference 0.12, 95% CI 0.09–0.15). A second experiment found that an intervening completion signal reduced reinstatement only when the signal was attributed to the transferred run, even when its pitch did not match the original signature. The results distinguish an outstanding terminal event from a learned association between a display and a sound.

Events usually change their sensory appearance and their purpose at about the same time. A hand comes to rest when it has set down an object. Speech pauses when a turn ends. The agreement between these boundaries makes an otherwise useful feature of natural actions difficult to identify experimentally. An observer who predicts the last sound of an event may have learned the acoustics of the apparatus, the structure of the action, or both. Studies of segmentation distinguish updates to an event model from sensory transients, and studies of auditory omission find responses at the moment a predicted sound should have occurred[1–4]. Neither result establishes what happens when the source of a terminal sound and the activity it terminates are physically separated.

We looked for an everyday event whose final acoustic transition could be almost completely removed while a numerical record of the remaining interval was still visible. Microwave ovens meet this requirement. When a run is interrupted with one second showing, the practical work may be regarded as finished, and the display can return to its clock. The completion tone has nevertheless remained unplayed. What remains unclear is whether the omitted beep is specifically a beep of the first appliance, a beep of whichever appliance is next encountered, or a sound still assigned to the original run. Observational accounts record pauses at displays showing one second, but a pause in front of the source machine provides no leverage on the distinction[5,6].

Here we present two disconnected microwave interfaces with different acoustic signatures, used in succession. Our participants watched a parcel leave the first interface with one second remaining. A continuation cue identified the run on the second interface as either the unfinished run or an unrelated run with one second on its dial. All outcome trials were silent and groups saw the same countdown. The acoustic decoder had seen neither display. This separation was necessary because an omitted sound can yield a deflection that reflects surprise at the silence, even when the signal carries no information about the sound that should have been heard[7,8]. Signed discrimination between two candidate pitches provides a way to test for that information.

Results

A silent terminal window carries the source frequency

The enrollment and analysis counts are in Table 1. Both sites used the same trial generator and recorded the same two within-participant experiments. The silent test trials in the first experiment crossed two independently assigned appliance pitches with three relations between the interrupted run and the final display. The transfer condition kept the parcel's outstanding run. In substitution, the first parcel was withdrawn and a new one was assigned to the final display. In acknowledgment, the original parcel moved to the final display after an explicit silent completion receipt, and the second run was fresh. Physical sounds and countdown frames during the interval analyzed below were identical across these conditions. The receipts and relation cues preceded that interval.

Table 1 | Participant accounting by recording site. Exclusion categories are disjoint and apply to both experiments.

Site	Enrolled	Incomplete visit	Mapping criterion missed	EEG trial criterion missed	Analyzed
Grenoble	40	1	1	2	36
Sendai	40	0	2	2	36
Total	80	1	3	4	72

Frequency decoding in the separate sound localizer yielded a mean area under the receiver operating characteristic curve (AUC) of 0.79 (95% CI 0.76–0.82) at 90–170 ms. We evaluated each person's fitted decoder through the silent interval at the recipient display, first using the source frequency as the label. The rise in Fig. 1 began near the expected tone, with little source discrimination at negative latencies. In the prespecified 100–220 ms summary window following the scheduled tone, transfer AUC was 0.62. Substitution gave 0.50 and acknowledgment 0.51. The paired transfer–substitution difference was 0.12 (0.09–0.15). Site estimates of

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that contrast were 0.13 (0.08–0.18) in Grenoble and 0.11 (0.07–0.15) in Sendai. Site sample sizes were identical, so the regional means average to the pooled estimate before rounding.

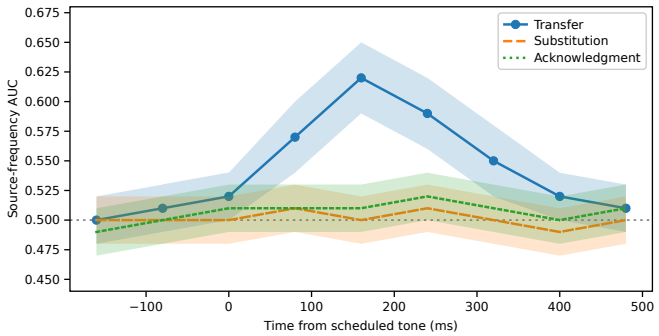


Fig. 1 | Source-frequency decoding around the silent endpoint. Each point shows a 40-ms window centered at the stated latency. Bands indicate pointwise 95% participant-bootstrap intervals. The primary AUC is computed on a mean score over 100–220 ms before ranking.

At substitution, the same decoder, scored against the frequency of the final display rather than that of the initial one, gave 0.60 (0.57–0.63). The reciprocal analysis during transfer gave 0.51 (0.49–0.53). Estimates stratified by the other frequency are given in Table 2. This matters for the low-frequency source trials. Half of those trials had a high-frequency recipient, so a low score could correspond to either retention of the source signature or suppression of a competing recipient signature. The same estimate for source frequency within fixed recipient labels rules out a contrast made solely by choosing different proportions of recipient labels across conditions.

Table 2 | Frequency discrimination in the silent window. Intervals are pointwise 95% bootstrap intervals over participants. AUCs condition on the other label before averaging.

Experiment and condition	Source-frequency AUC	Recipient-frequency AUC
1, transfer	0.62 (0.59–0.65)	0.51 (0.49–0.53)
1, substitution	0.50 (0.48–0.52)	0.60 (0.57–0.63)
1, acknowledgment	0.51 (0.49–0.53)	0.59 (0.56–0.62)
2, intervening signal assigned to another run	0.60 (0.57–0.63)	0.51 (0.49–0.53)
2, intervening signal assigned to the source run	0.52 (0.50–0.54)	0.51 (0.49–0.53)

On silent trials without a delayed question, the transfer–substitution contrast was 0.11 (0.08–0.15). The identity of the probe was unknown in the neural analysis window. On trials with a pitch question, participants selected the source pitch on 72% (68–76%) of opposing-pitch transfer trials and 30% (27–33%) of the corresponding substitution trials (Fig. 2). Opposing pitches were needed here because a single answer cannot distinguish source and recipient when they sound the same. Since these proportions come from explicit judgments, we use them to establish what participants understood the displays to represent. They do not measure reports of hearing a tone.

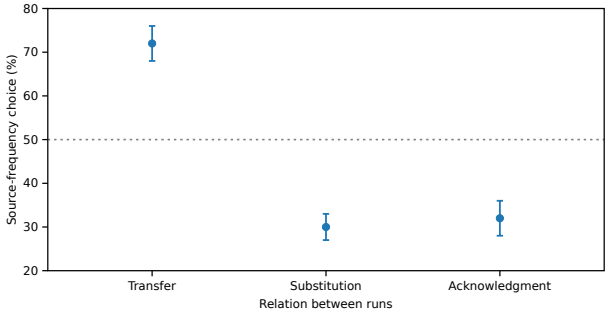


Fig. 2 | Responses on trials where the two interfaces had opposite pitches. Points are participant means with 95% bootstrap intervals. The two choices were recordings of the two localizer frequencies; participants were asked which tone would have fitted the trial if a tone had played at the endpoint.

Attribution of an earlier sound releases the representation

A display may still show one second if a status record was not cleared. The apparent unit of time is therefore a poor test of what constitutes completion. In Experiment 2, the first parcel and its outstanding run always moved to the second display. During the gap, all trials included the *other* pitch relative to the source, an ordinary terminal tone played through the same headphones. A subsequent attribution cue said it had closed either the transferred run or another run outside the display. The recipient still displayed one second, and the same visual sequence ended silently. If a signature were simply held until its scheduled position, a different pitch at an earlier time would have the same effect under either attribution.

The source decoder discriminated at 0.60 when the intervening tone was attributed elsewhere. When it was attributed to the transferred run, discrimination was 0.52. The paired difference was 0.08 (0.05–0.11). We estimated the attribution effect also after splitting by the source pitch and scoring the continuous, sign-aligned decision value. Fig. 3 shows the mean standardized score for each pitch. The directional agreement matters because the intervening tone was always opposite to the source: adaptation could make the omitted tone's template easier or harder to detect, but that acoustic relationship was identical in the two arms. The attribution fork occurred after tone offset.

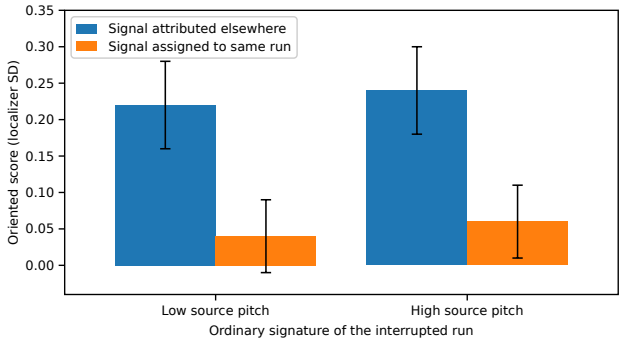


Fig. 3 | Reinstatement score following identical intervening tones. Scores were oriented toward the source frequency and standardized with each participant's localizer score dispersion. Error bars indicate pointwise 95% participant-bootstrap intervals.

The attribution cue was randomized independently of device color, starting side and frequency. Visual cue identity was reversed in alternating blocks. A classifier trained to distinguish the two physical attribution symbols decoded them during their presentation but was uninformative about source pitch in the terminal window (AUC 0.50, 0.48–0.52). This visual control had a different training target from the sound localizer and is informative chiefly about a fixed symbol confound. A cue that is read correctly could still change the content of a person's imagery.

Discussion

The two tests give different ways to dissociate completion from the remaining digit. In the first, a receipt can put an end to the first run without supplying the expected sound. In the second, a sound can put an end to the same run despite supplying the wrong frequency. In both cases the second interface still carries out its visible final second. The two dissociations point to an assignment problem, namely which terminal event applies to which run. Many accounts of event models give goal changes a role in state updating[9,10]. They leave open whether the details of an expected sound can survive reassignment of the equipment used in an event. The temporary survival of a frequency representation is consistent with that possibility.

It is tempting to call an unresolved second an interval of waiting. This would predict that extending the gap before the recipient countdown should either evoke the tone at the original deadline or gradually erase the expectation. In our data the silent maximum was aligned to the new deadline. An analysis split at the median gap showed source AUCs of 0.63 and 0.61 in the short and long bins, with a difference of 0.02 (−0.01–0.05). A pair of gap durations differentiated by less than a second is insufficient to delimit retention. The useful observation is that the longer trials had already passed the end of the first appliance’s scheduled interval when the source signature became discriminable at the second. Setting one second aside did not make it elapse in the ordinary sense.

The experiment distinguishes a deferred event from a prediction triggered by the current appliance. It gives less purchase on the mechanism maintaining the event. A participant might retrieve the tone when shown the relation cue, hold a verbal or musical label, then imagine it at zero. An attention-based account of some omission responses remains viable[11]. Inferring sensory content from a cross-decoder is also limited by shared signal geometry. A frequency discriminant can align with activity associated with hearing, expecting or remembering the training frequency. We did not attempt to separate these possibilities by asking about awareness during EEG recording. A forced choice between two sounds is compatible with all of them.

We used a single observation mode deliberately. None of the appliances was physically present and the parcel was drawn. In a kitchen, a door opens, an interior fan changes pitch and the object can be taken away. Such events provide independent boundary evidence[12]. Noise can mask a real terminal signal or induce a cue that was absent from the recording. The substitute and receipt conditions establish contrasts for the task with the cues available here. They do not establish that people bring a source signature to every visually similar appliance that they subsequently encounter.

There is a related ambiguity about the word *completion*. A perceptual account could maintain the association between the parcel and the first interface until a relation cue breaks it. An event account could maintain a pending auditory terminal token even while the parcel’s source association is intact. The acknowledgment condition was designed to keep parcel continuity while ending the expectation. Its results favor the pending token interpretation. They do not rule out cue-dependent retrieval of one among several stored parcel attributes. A useful next dissociation would be to probe the remembered source frequency after receipt at a time when no terminal cue is due. Intact source recall in that setting would make the loss of reinstatement on a scheduled terminal trial more informative about closure.

Methods

Participants and ethics

Eighty adults aged 19–52 years enrolled, 40 at each site. The feasibility sessions used to set trial length and freezing criteria involved 12 different participants. For planning we assumed a standard deviation of 0.22 for the participant-level paired AUC difference, rounded up from the feasibility estimate. With 72 analyzable participants this gave 90% normal-approximation power for a difference of 0.085 at a two-sided 5% level. We stopped enrollment at 80 irrespective of accuracy. The study was approved by the Institut des Sciences Cognitives de l’Isère committee and its Kiyohara counterpart (ICII-24-019 and KIB-2024-06). Participants consented to recording and to sharing derived trial scores. The analyses exclude visits without both experiments, failure on the recorded mapping check before either outcome block, and insufficient clean trial counts as listed in Table 1. Criteria were applied before inspecting condition means.

Stimulus and run assignment

Video was built from a set of vector interface states. Each participant learned four front panels, counterbalanced in pairs between 740 and 1,110 Hz. Tones had 120-ms duration with symmetric onset and offset ramps. Assignment to screen side varied by trial. Source and recipient were chosen with replacement from the two pitch classes, with different physical panels used even when their pitches agreed. Training continued for one fixed set of 48 named-panel trials. A subsequent 24-item mapping check gave the panel names and required a pitch choice. The criterion was 20 correct answers. Test instructions emphasized parcel identity and run continuity. They gave no rule for choosing an endpoint pitch after a transfer.

Each Experiment 1 trial began with a three-second source countdown, interrupted at the beginning of its last nominal second. A masked interdisplay interval of 1.6, 1.8, 2.0 or 2.2 s followed, randomized in equal proportions. The parcel icon passed behind a divider. At 400 ms after interruption, a learned symbol set its relation to the second display. One symbol stated that the earlier operation continued. In the substitution condition a different parcel had entered while the divider was closed. In acknowledgment the original parcel was carried across after its original run was marked complete, and the recipient display initiated a new run. The symbol remained for 350 ms and disappeared before the recipient’s one-second countdown. Receipt was indicated by a symbol of the same duration and visual area, with symbol mappings changed between blocks. The displayed digits and housings were drawn on a fixed luminance background. A photodiode measured the frame marking zero. Headphone output was recorded on an acquisition channel so that a trial with an unintended sound could not count as an omission. No outcome stimuli were selected from trials after looking at EEG scores.

Every participant saw 144 scheduled silent trials in Experiment 1 (12 per relation by ordered pitch pair), plus 72 audible fillers. Filler tones occurred at the visual endpoint and the pitch was randomized within relation, so no tone associated with a relation was taught by its filler outcomes. Blocks interleaved conditions with constraints on cell totals. A quarter of scheduled silent trials ended in a delayed two-alternative counterfactual pitch question, 750 ms after the terminal event. Other trials ended with a question about panel orientation or no question. Choice sides were randomized after EEG collection for the trial window. We used the counterfactual question wording in Fig. 2 to avoid classifying inferred endpoints as perceptual reports[13].

Experiment 2 used 96 silent endpoint trials, with 12 per attribution by ordered pitch pair, and 48 matching filler trials with a tone at zero. The intervening opposite pitch was sampled from the same waveform set as the fillers. It began 750 ms after interruption and the attribution symbol appeared 250 ms after that tone’s onset. The icon crossing the divider belonged to the source run in both conditions. If the intervening sound was assigned to that run, it was marked complete, even though the display on the recipient still ran from one second to zero. The alternative relation was an intervening tone from a separately ending run; no third display appeared. Experiment order was counterbalanced. The attribution experiment was specified as a secondary, within-cohort test.

EEG and frequency localizer

Each visit began with an independent 200-trial listening block in which the two tones had equal probability. Fixation was the only image during tones. The task was to report occasional changes to fixation color near the end of a trial, allowing collection of sound-evoked EEG without asking for

a response to the pitch. We digitized 64 common scalp channels at 1 kHz and resampled to 250 Hz after anti-alias filtering. Photodiode and headphone triggers were checked against presentation logs. Data were filtered from 0.1 to 30 Hz with a forward-backward filter; the pre-event time course is therefore descriptive. The primary endpoint follows zero and conditions were silent for at least 1 s around zero. An equivalent analysis with a causal low-pass produced a transfer–substitution AUC difference of 0.11 (0.08–0.14).

We removed components dominated by independently recorded eye channels using infomax ICA and the labeled EOG correlation rule[14]. Trial rejection used fixed peak-to-peak voltage limits applied to the same electrodes and epoch lengths in each condition. Channels rejected on a minimum of 25% of trials were interpolated before common average referencing, with at most six channels interpolated per participant. Baselines were the 200-ms epochs immediately before the scheduled acoustic endpoint or localizer tone. A participant required at least six silent trials in each condition by ordered pitch cell and at least 65 clean localizer trials per pitch. The trial thresholds constrain reportable discrimination by cell and guard against an apparent effect based on a handful of epochs.

Endpoint estimands and uncertainty

We used participant-specific ridge logistic decoders fit to channel means over 90–170 ms in the localizer. The penalty was fixed from the feasibility sample. The descriptive localizer AUC used stratified ten-fold evaluation; the decoder taken to the main task was refit on all clean localizer trials. Channel centering and scaling from the localizer training data were applied to the task. Independent training matters here because differently signed task-specific classifiers could give above-chance AUC for visual cues with no relation to auditory frequency[15,16].

We denote a localizer-trained high-frequency score on epoch i by s_i. For condition c, the source AUC for each participant averages rank probabilities within both recipient labels r:

$$A_c = \frac{1}{2} \sum_{r \in \{L,H\}} \left[\Pr(s_{H,r,c} > s_{L,r,c}) + \frac{1}{2} \Pr(s_{H,r,c} = s_{L,r,c}) \right]. \quad (1)$$

Indices H and L here refer to source frequency and the compared epochs are drawn independently from their corresponding retained cells. We exchange the two frequency indices for the recipient AUC. equation (1) is estimated by the finite-sample rank statistic[17]. Positive scores indicate a high-frequency tilt. For the signed plot in Fig. 3, we multiply the centered score by $+1$ for a high source frequency and -1 for a low source frequency, then divide it by the standard deviation of the localizer's two within-pitch score distributions pooled within participant. The localizer center is the equal-weight mean of its two pitch classes. This makes the two pitch strata comparable in the plot without using task-label centering.

The confirmatory contrast is

$$\widehat{\Delta} = \frac{1}{72} \sum_{p=1}^{72} \left(A_{p,\mathrm{transfer}} - A_{p,\mathrm{substitution}} \right), \quad (2)$$

with the definitions in Results. For equation (2) and the accompanying summary intervals, we drew 10,000 paired bootstrap resamples, preserving the site counts. Percentile endpoints use the sorted bootstrap values[18]. Pairing preserves person-specific decoder quality in the subtraction. Individual feature coefficients were used only for classification; an electrode's decoding weight is not interpretable as a voltage map[16]. The primary window was set with the feasibility sample, and the other windows in Fig. 1 are unadjusted descriptive estimates. The comparison of attributions in Experiment 2 had a single prespecified contrast and is reported with its own unadjusted interval. We use neither plot to find additional significant onset latencies[19].

Fixed checks and deviations

It was permissible for the first tone's pitch to recur at the recipient if the panels differed, and those trials remained in the estimator. To check that conditioning in equation (1) did not hide competition between the two frequencies we recomputed discrimination separately at each recipient pitch. With a low-pitch recipient the source contrast in equation (2) was 0.11 (0.07–0.15), and with a high-pitch recipient it was 0.13 (0.09–0.17). Removing participants with above-median dropout produced a contrast of 0.12 (0.08–0.16). The two site samples and the median split were defined before fitting any participant decoder.

After a timing check at Grenoble we moved the question onset one frame later for seven participants to resolve a display scheduling issue. The silent terminal windows all preceded the question and used the actual photodiode time. Excluding those seven gives a mean contrast of 0.12 (0.09–0.15). Classification from the bipolar EOG channels, trained on the localizer using the same passband, yielded a transfer AUC of 0.50 (0.48–0.52). The EOG check addresses the possibility of eye movements that produce a frequency-specific localizer signature.

Data and code availability

Derived epoch scores, stimulus event logs without absolute timestamps, and analysis scripts are available from the corresponding author. The consent agreement does not cover public release of the raw EEG. The stimulus package contains the four panel drawings and the timing state table, including the transfer, substitution and acknowledgment relations. It contains no appliance-control software.

Author contributions

C.M.-L. and S.N.M.-T. designed the study. T.U.-N. and C.M.-L. supervised data collection. R.E.-D. implemented the stimulus timing controls and independently reproduced the rank estimates. C.M.-L. wrote the first draft. All authors reviewed the analysis and manuscript.

Competing interests

The authors declare no competing interests.

The role of a visible zero

A display may end a run by going blank before zero is observed. We tested this with a supplementary block of 32 trials per participant, with the countdown frame absent at the expected boundary on every trial. The time base remained defined by onset of the recipient's one-second frame. Scoring the fixed primary window gave AUC 0.57 (0.54–0.60) in transfer and 0.50 (0.47–0.53) in substitution. Their difference was 0.07 (0.03–0.11). The supplementary block had only four trials per condition by ordered pitch pair before rejection. To avoid unstable or missing within-stratum ranks, this block used unconditional rank estimates and included the 70 participants with at least one surviving trial in each cell. Pitch pairs were balanced by random subsampling within participant using a fixed seed. Thus its difference from the 0.12 estimate in equation (2) combines both a rendering manipulation and a change in estimation. The result establishes that visible onset of zero was dispensable in this subset. Its precision is insufficient to decide whether foreknowledge of when zero ought to appear accounts for the smaller estimate[20]. A zero frame could be a valid gain cue for the auditory representation without serving as its content.

Acknowledgements We thank Lidia Perchan and Kosei Tomomura for testing the photodiode alignment. The West Rhone Perception Fund supported the common stimulus build.

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