Metacognition in second language speech perception and production

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Abstract

The current work assessed metacognition in non-native language speech perception and production. Spanish novice learners of French identified and produced French vowel contrast /ø/-/œ/ and rated, on each trial, their confidence in the response. Confidence in perception predicted participants' identification accuracy, suggesting that novice learners' metacognitive skills in non-native speech perception are efficient at the onset of language learning. However, confidence in production did not align with a fine-grained precision measure of one's own production - indexed by Mahalanobis distance to the native French target-vowel space, nor with a categorical measure of production - in terms of being within/ outside the native-speakers' zone - indicating metacognition in non-native sound productions is not yet efficient in novice learners. Overall, confidence ratings were similar and highly correlated between the perception and production tasks, but there was no association between the two domains in task performance or metacognitive ability. We discuss the ramifications of these findings for language learning theories and language teaching strategies, as well as the ongoing debate on the perception-production relationship.

Introduction

Metacognition is the process that allows us to reflect on and evaluate our own cognitive processes and performance in different tasks, including knowledge about the task and strategies needed to successfully achieve it (Flavell, 1979). Metacognitive evaluations come with a judgement of confidence that reflects the likelihood of a behavioural response to be correct (Maniscalco & Lau, 2012). In other words, metacognition is one's ability to be more confident in correct relative to incorrect responses.

Metacognition has been extensively studied in sensory perception (Fleming & Dolan, 2012; Jachs et al., 2015; Peters & Lau, 2015) and memory (Koriat, 2019; Koriat et al., 2006; Koriat & Shitzer-Reichert, 2002; Kuhlmann, 2019), demonstrating that people generally have good introspective access to the quality of their behavioural responses in perception and memory tasks: self-reported confidence in the task at hand was typically higher for correct than for incorrect choices. These studies suggest that metacognition, through one's sense of confidence, is used to monitor individuals' performance, and may also promote the development of adaptive strategies to control behaviour and learning (Nelson & Narens, 1994). Although metacognition has been extensively examined in attention and memory, the role of metacognition in language remains to be systematically evaluated. In particular, there is a gap in the understanding of the role of metacognition in foreign language learning, specifically how language learners monitor the correctness of their responses in linguistic tasks and whether the resulting meta-knowledge can guide

optimal learning strategies. The current study, therefore, investigated metacognition in language across two domains: speech sound perception and production.

The current study focused on novice language learners and the role of metacognition within non-native sound perception and production. Foreign language learners typically display wide between- and within-speaker variability in their ability to accurately produce and perceive non-native speech sounds. This is helpful when it comes to assessing metacognitive skills because it avoids ceiling effects likely observed in native production (Bradlow et al., 1997; Flege & Schmidt, 1995; Hanulíková et al., 2012; Nagle, 2018). Very little research has examined metacognition (i.e., how one's confidence tracks the quality of behavioural responses) in perception and production of non-native/second language (L2) speech sounds, as compared to larger linguistic units, e.g., sentences, texts and monologues. In earlier research, Yule and colleagues (Yule, Damico, et al., 1987) reported that L2 learners' self-monitoring ability to correctly identify L2 minimal word pairs was stronger in experienced learners - who have undergone some formal learning - as compared to early-stage learners. In another study, the same team (Yule, Hoffman, et al., 1987) investigated the effect of pronunciation-and-listening training on L2 learners' accuracy in phoneme identification using confidence ratings. The results showed considerable variation among participants in the size of the training effect on perceptual accuracy and also on the extent to which self-confidence ratings tracked response correctness (Yule, Damico, et al., 1987).

In the production domain, Dlaska and Krekeler (2008) studied the ability of advanced learners of German to monitor the quality of their speech production in comparison to the evaluations made by a native speaker. They found an overall correspondence between learners' self-assessments and the raters' assessments when the productions were indeed correct. However, learners had difficulties to recognise as incorrect a considerable number of productions, indicating that metacognitive monitoring of L2 speech production is not fully reliable. A recent study, also in German speakers, suggested that L2 learners, although aware of their accents in production, tend to overall judge their own production as less accented than those of other speakers of their language, and to understand L2 words better when produced in their own voice, as compared to that of other speakers (Eger & Reinisch, 2019). This is proposed to be due to more frequent exposure to their own productions, yielding less objectivity in their assessment (Mitterer et al., 2020). In line with this, a recent study showed that L2 speakers tend to misjudge their L2 skills: those who perform poorly overestimate their pronunciation skills, whereas those who perform highly underestimate them (Trofimovich et al., 2016). This is reminiscent of the Dunning-Kruger effect, in which inexperienced people think they are better at cognitive or behavioural tasks than they truly are (Kruger & Dunning, 1999). Yet, experienced L2 speakers appear to have a more robust/clear overall estimation of their L2 production abilities, as their self-estimated pronunciation correlates strongly with the overall nativelikeness of their L2 production and with the accuracy in the production of specific L2 sounds, although to a lesser extent (Peperkamp & Bouchon, 2011).

Our review of a handful of studies on self-monitoring in L2 pronunciation and sound perception revealed inconsistent findings, which could partly be attributed to differences in the unit of analysis (text vs segment), measures or methods to assess L2 production (objective acoustic measures vs perceptual ratings) and L2 proficiency (novice vs experienced). To the best of our knowledge, there is a lack of research using objective measures of L2 production and, importantly, no studies examining metacognition in both L2 sound perception and production within the same experimental setting. Furthermore, prior work reviewed above did not address the trial-by-trial wise relationship between confidence-based self-monitoring and accuracy. In the current study, we used objective measures to assess accuracy in non-native speech sound production, and we assessed, within the same experimental setting, comparable levels of processing (i.e., phonemic) across the two language domains. Here, we hypothesised that metacognition in novice learners would be reflected in a positive relationship between participants' trial-by-trial confidence ratings and their accuracy in L2 perception and production performance. We expected the current study to be more sensitive to pinpoint confidence-based metacognitive monitoring, even in novice learners.

In addition to providing insights on metacognitive processes in language perception and production, examining metacognition in two language domains will also shed light on an unsettled debate on the nature of metacognition, i.e., whether it is domain-specific or domain-general. A number of studies suggest that metacognition operates at a domain-general level. Inter-individual variability in the level of metacognitive sensitivity (i.e., how

well confidence tracks trial-by-trial accuracy in the task), or associated neural markers of metacognition, have been shown to correlate across different task domains (e.g., perception and memory), suggesting a domain-general metacognitive system (Ais et al., 2016; Baird et al., 2013; McCurdy et al., 2013; Morales et al., 2018; Samaha & Postle, 2017). The comparison of metacognitive performance across language perception and production would provide knowledge on the organisation/structure of metacognition in language. If we observe that inter-individual variation in metacognitive ability in perception is correlated with that of production, then we would conclude that both language domains are likely supported by a shared metacognitive system.

The final goal of our study was to examine the relationship between phonemic perception and production. This topic is of a particular relevance to research on non-native/L2 processing. Late L2 learners often experience difficulties in their perception and production of non-native speech sounds, commonly revealed by their difficulties in discrimination of L2 contrasts (e.g., ‘lock’ vs ‘rock’ for Japanese learners of English) and their mispronunciation of L2 speech sounds (e.g., /i/ instead of /ɪ/ in ‘ship’ in Spanish learners of English, e.g., Flege et al., 1997). Although the dominant theoretical perspectives attribute L2 speakers’ difficulties in production to a lack of accurate perceptual representations for L2 sounds and predict a tight relationship between the two domains (Best, 1995; Best & Tyler, 2007; Flege, 1995), research provides no evidence for a consistent relationship between L2 speech sound perception and production (Bradlow et al., 1997; Flege, 1995; Flege & Eefting, 1987b; Hanulíková et al., 2012; Hattori & Iverson, 2010;

Kartushina & Frauenfelder, 2014; Nagle, 2018; Nagle & Baese-Berk, 2021; Okuno & Hardison, 2016; Peperkamp & Bouchon, 2011; Sheldon & Strange, 1982). The strength of the relationship is modulated by a number of factors, ranging from L2 experience and proficiency (Bohn & Flege, 1997; Jia et al., 2006; Rallo Fabra & Romero, 2012), to the level of linguistic processing explored (e.g., prelexical, phonological, lexical, see Bohn & Flege, 1997; Hao & de Jong, 2016; Melnik-Leroy et al., 2021; Peperkamp & Bouchon, 2011), L2 sound difficulty (similar to vs distinct from native categories, e.g., Bohn & Flege, 1992; Evans & Alshangiti, 2018; Hao & de Jong, 2016; Levy, 2009; Levy & Law, 2010; Nagle, 2018) and L2 production accuracy measures (e.g., intelligibility ratings vs acoustic analyses, Evans & Alshangiti, 2018; Flege et al., 1999; Hattori & Iverson, 2010; Inceoglu, 2019). Therefore, to better understand the relationship between L2 perception and production, there must be strict and systematic control of the participants' linguistic experience, the difficulty of the L2 sounds, and the tasks and measures to assess L2 production. The current study attempted to control for these factors (see below).

To achieve the above-mentioned goals, we examined novice Spanish speakers' perception and production of the French vowel contrast /ø/-/œ/ and assessed, on a trial-by-trial basis, their self-confidence in performance. Previous research (Kartushina & Frauenfelder, 2014) has shown that Spanish speakers experience difficulties in discriminating these two vowels in both perception and production, suggesting that they perceptually assimilate them both to one new phoneme, dissimilar from Spanish categories, as shown in Figure 1. Both the Speech Learning Model (SLM, Flege, 1995) and the

Perceptual Assimilation Model (PAM, Best, 1995) agree that L2 sounds are processed as a function of their perceived similarity to close L1 categories and to each other and predict that participants' perception and production of the /ø/-/œ/ contrast will vary from poor to intermediate as a function of individuals' perceived proximity of the /ø/-/œ/ vowels to each other. In the present study, participants were familiarised with the target vowels /ø/-/œ/ and their respective labels through an auditory exposure to consonant-vowel (CV) words containing the target vowels. Then they performed, in a counterbalanced order, vowel identification and vowel reading tasks, including trial-by-trial confidence ratings of self-performance (Figure 2). This experimental design allowed us to study the relationship between L2 speech sound perception and production both at the level of primary task performance and also metacognitive performance by systematically controlling several factors: L2 experience (all novice learners), level of processing assessed in both modalities (prelexical), no perceptual component in the production task, type of input during the exposure (identical familiarisation for all participants) and type of L2 sounds (non-native French vowels not present in the Spanish vowel inventory). In light of previous research and the above-mentioned specificities in the current design, we expected to find a relationship between L2 speech sound perception and production; however, the relationship might be weak, as we tested novice learners.

Methods

Participants

Forty-five native Spanish speakers with no experience in French were recruited, via the laboratory participant database, to take part in the study. Nine participants were excluded from the study, due to technical reasons with the recording of the productions ($n = 5$) or to participants' failure to follow the instructions, as they were not providing confidence ratings on more than half of the trials ($n = 4$). The final sample consisted of 36 speakers ($M = 23$ years, 22 females) with normal hearing, as reported by participants. All participants provided consent prior to the experiment and received remuneration for taking part in the study. The project was approved by the BCBL Research Ethics Board.

Stimuli

Stimuli consisted of French word pairsⁱ featuring /ø/-/œ/ vowels. A female native French speaker read aloud 5 word pairs featuring the target vowels in five different consonant contexts (in manner and place of articulation), all of which exist in Spanish and are perceptually close to French: /dø/-/dœ/, /kø/-/kœ/, /fø/-/fœ/, /lø/-/lœ/, /pø/-/pœ/ (deux-odeur two-smell, queue-cœur line-heart, feu-feur fire-non-word, leu-leur leu (the currency in Roumania) -their, peu-peur little-fear). The speaker repeated each word five times, yielding a total of 50 stimuli which were used in the vowel identification task. Exactly the same CV stimuli (dø-dœ, kø-kœ, fø-fœ, lø-lœ, pø-pœ) were used in the word reading task (henceforth, we refer to it as “non-word” reading task, as participants were unfamiliar with these words).

Additionally, five other female native French speakers read aloud a word pair featuring the target contrast in a different, 6th /s/, context: /sø/-/sœ/ (ceux-sœur those-

sister). Each speaker repeated the word pair twice, yielding 20 stimuli which were used in the familiarisation task. In the current design, we wanted to encourage participants to rely mostly on abstract phonological representations, as compared to a pure acoustic comparison of speech sounds. Yet, short words, as used in the current study can easily be compared at a purely acoustic level and result in ceiling performance. That is why, in the familiarisation task, we opted for a single-consonant but multiple-talker context (as the /s_/ frame was produced by five native French speakers), whereas in the identification task, we included contextual variability, to maximise the reliance on a more abstract representational level. An additional reason was to homogenise the stimuli between the production and perception tasks; please note that by using untrained consonant contexts in the production task we were able to examine spontaneous production (as opposed to retrieval of a heard trace from the auditory memory).

All stimuli were recorded with a Marantz PMD670 portable recorder, and the recordings were sampled at 22.05 kHz directly to 16-bit stereo .wav files. The CV segments were manually extracted in Praat (Boersma & Weenink, 2020) and equalised to 65 dB amplitude. The first 20 and last 50 ms were ramped. To examine the distribution of /ø/-/œ/ vowel exemplars in the acoustic vowel space, we measured the average first two vowel formants (F1 and F2), using Praat default settings for female voice (max formants 5500, 5 formants). Formant frequencies in Hz were converted to Bark (Traunmüller, 1997) and adapted for female voice, following Bladon and colleagues' formula $(26.81 \times F / 1960 + F) - 1.53$ (Bladon et al., 1984). Figure 1 illustrates the target French vowels compared to the Spanish

norms (Chládková & Escudero, 2012). Importantly, the target French vowels had formant values comparable to the norms previously reported for native French female speakers (e.g., Georgetown et al., 2012).

Figure 1. Distribution of the French vowel tokens used in the tasks and the Spanish norms, for comparison (Chládková & Escudero, 2012). [Colour figure can be viewed at wileyonlinelibrary.com]

Procedure

Native Spanish speakers' self-confidence in perception and production of the French contrast /ø/-/œ/ was assessed in a three-step procedure, via DMDX software (Forster & Forster, 2003). First, participants were familiarised with the target vowels: on each trial,

they heard one of the CV syllables, ‘sø’ or ‘sœ’, and saw it written (in phonetic symbols) on the screen, with the target vowel highlighted in red. Their task was to learn the two novel vowel-label associations. There were 20 familiarisation trials. Given that there were only 2 labels to learn and based on the results of our pilot tests, 20 trials seemed enough to learn the 2 sound-label associations. As we shall see below, the results in the perception task demonstrate that participants were above chance demonstrating that they learnt the labels after the familiarisation phase. Immediately after the familiarisation phase, participants proceeded, in a counterbalanced order, to the two remaining tasks: a phoneme identification and a reading task. During both tasks, participants wore Sennheiser Pro headphones fitted with a microphone that was used to deliver auditory stimuli and to record productions.

Identification task

In the perceptual (identification) task, on each trial, participants heard one of the target vowels embedded in a CV context (cf Stimuli), and had to identify it by pressing a button with the corresponding label (“ø” or “œ”). Immediately after providing an answer, or at the end of a 3000-ms timeout (if no answer was provided), participants were asked to indicate how confident they were in the accuracy of their identification on a scale from 1 (I answered completely at chance) to 6 (I am completely sure). Participants were instructed to answer as quickly/intuitively as possible and within a timeout of 2500 ms (see Figure 2 for an illustration). Upon providing an answer or at the end of the timeout, a 500-ms black screen was displayed before presenting the next trial. There were 200 trials in total,

distributed across 4 randomly presented blocks of 50 unique (unrepeated) trials. Therefore, each singular token was presented 4 times, and each vowel was displayed 100 times: 4 blocks * 5 consonant contexts * 5 speakers. The order of trials within each block was random. Participants were offered to take a break between the blocks, if desired.

Figure 2. English translation of the visual aids displayed on the screen for the

identification and reading tasks. In each of these tasks, on each trial, participants had to, first, either press a button with the correct label or read a displayed CV word, and then indicate the degree of confidence in their answer. The original material can be viewed on the project's OSF page <https://bit.ly/3Dqsf2s>. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

Reading task

In the reading task, similarly to the perception (identification) task, participants had to perform two actions: They had to read a written CV non-word, consisting of a consonant and one of the novel vowel labels (“ø” or “æ”), and then to indicate the degree of self-confidence in the accuracy of their production/reading of the novel vowel (cf Figure 2). On each trial, participants saw a visual aid instructing them to read a non-word, which was followed, 3000 ms later, by a self-confidence rating display that prompted participants to report their degree of confidence on a 6-point scale, as in the perception task. The timeout, again, was set to 2500 ms. Upon providing an answer or at the end of the timeout, a 500-ms black screen was displayed before presenting the next trial. There were 200 trials in total, distributed across randomly presented 4 blocks of 50 trials. Therefore, each vowel was produced 100 times: 4 blocks * 5 consonant contexts * 5 repetitions.

Data processing

Identification task

Participants’ accurate answers in the perceptual (identification) task were coded as 1 and incorrect answers were coded as 0. Confidence rating scores ranged between 1 and 6. Trials with no answers were removed from the analyses (1.07 % of the data).

Reading task

Individual audio recordings of participants’ productions in the CV non-word reading task (N = 7200) underwent a four-stage processing. First, they were denoised. Second, we used a customised consonant-sensitive Matlab script to detect, for each word,

vowel onset and offset, which were visually checked, on a spectrogram, and adjusted in Praat, if necessary (this concerned 2.5% of data). Third, we computed the first two vowel formants, F1 and F2, over the whole vowel duration, using the same automatized Praat script as the one utilised to process native French speakers' productions (see Stimuli). 44 vowels were estimated manually, as they were too short. Audio recordings containing coughs, sighs, laughs or silence were removed from the analyses (N = 178, 0.024% of the data). Following the same procedure as for the stimuli, formant frequencies in Hz were converted to Bark. Participants' individual vowel productions in the acoustic F1/F2 space are represented in Figure 3.

Figure 3. Participants' individual productions of the French /ø/ and /œ/ vowels (marked as “eu” and “oe” in the legend) in the acoustic F1/F2 space (in Bark), compared to native French speakers (Native_French).

Finally, in order to assess participants' accuracy in the production of novel French vowels, similar to previous studies (Franken et al., 2017; Kartushina et al., 2015, 2016; Kartushina & Martin, 2019), we computed, in a customised Matlab script, for each vowel token and subject, the Mahalanobis distance (or distance score, DS) between this token and the target acoustic space, defined as the 20 vowel tokens produced by native French speakers used for exposure in the familiarisation phase. Mahalanobis distance (Mahalanobis, 1936) is a unitless, scale-invariant measure of distance, in terms of standard deviation, from a given point to a distribution, which, by default, takes into account non-circular shape of vowel categories and token distribution in the F1/F2 space. The Mahalanobis distance was computed for each individual vowel token; therefore, for each participant, there were 100 distance scores for each vowel category. After removing 9 outlying trials, the DSs ranged between 0 and 15 ($M = 4.06$, $SD = 2.46$). Note that the 50 vowel tokens produced by native French speakers (and used in the Identification task) were situated, on an average, at 1.2 DS units to the target space (the most distant production was at 2.35 DS units). Therefore, to dichotomize Spanish participants' accuracy in the production of French vowels, while accounting for the shape of the target vowel distribution, and to make it comparable to the binary accuracy measure used in the identification task, vowel tokens/productions with $DS < 2.5$ were categorised as within the

‘native-zone’, whereas vowel tokens with $DS > 2.5$ were categorised as outside the ‘native zone’, as indicated by the distribution of vowel tokens produced by native French speakers (recorded for the study), which fitted all into the 2.5 SD area. Note that formant values for the target vowels recorded in the current sample (i.e., defining the ‘native zone’) were comparable to the norms reported for native French female speakers (e.g., Georgetown et al., 2012). The proportion of vowel tokens produced by Spanish learners within the ‘native-zone’ was 32% (SD = 25%).

Confidence ratings in the production task ranged between 1 and 6. Trials with no responses in the production task were excluded from the analyses (0.94 % of the trials).

Data analyses

Data processing and analyses were conducted using Python scripts (version 3.7). Scikit-learn was used to fit the linear regression and the logistic regression to test the relationship between confidence and accuracy in perception and production tasks (see Appendix S1 for details).

Metacognitive ability in the identification task was also assessed by computing meta- d' . Meta- d' provides an assessment of the efficacy with which one’s confidence ratings discriminate between correct and incorrect responses (i.e., type-2 sensitivity). Meta- d' is a parametric estimation of the participants’ type-2 sensitivity which is computed by fitting a type-1 signal detection theoretic model to the observed type-2 performance data (Maniscalco and Lau, 2012) and estimating the type-2 ROC curves (i.e., based on the ratio

of type-2 hits - reporting high confidence when you are correct - and type-2 false alarms - reporting high confidence when you are incorrect). Meta-d' presents clear advantages over other metrics used to assess metacognition (i.e., the correlation between confidence and accuracy; see Fleming and Lau, 2014). In particular, meta-d' provides a measure of one's metacognitive sensitivity which is independent of individual biases in reporting high or low confidence. Also, both d' and meta-d' are in the same scale and can be compared directly, thereby allowing an assessment of one's metacognitive ability regarding the level of performance capacity. Readers can refer to Maniscalco and Lau (2012) for the specific computational procedure and analytical scripts developed.

Bayesian analyses were conducted in JASP (JASP team, 2020) with the default priors. For the Bayesian correlation tests, a default beta prior width of 1 was used. For the one-sample Bayesian t-tests, we performed robustness checks and verified that Bayes factorsⁱⁱ were robust to variations of the prior.

The normality assumption for the one-sample Student t tests that we performed was checked by using the Shapiro-Wilk test of normality, and when a deviation from normality was detected, we followed up the one-sample t test with Wilcoxon signed-rank tests. We used a two-tailed alpha level of .05 for all statistical tests.

Results

Primary task performance in non-native perception and production

First, we examined participants' primary task performance in perception (vowel identification) and reading tasks. For that, we computed, for each participant, an averaged identification (accuracy) and production (Mahalanobis distance -DS-) score. One-sample t-test on participants' identification accuracy revealed significant above 0.5 chance performance ($M = 0.69$, $SD = 0.16$; Lower CI = 0.637, Upper CI = 0.744, $t(35) = 7.205$, $p < 0.001$, $BF_{10} = 648248.39$, Cohen $d = 1.201$ -large effect size-, 95% CI: Lower=0.765, Upper=1.626). The same result was obtained with the perceptual sensitivity score - indexed by a bias-free, signal detection measure d' computed as $z(\text{hit rate}) - z(\text{false alarm rate})$, where a 'hit' is responding "ø" when an /ø/ was actually presented and a 'false alarm' is responding "ø" when an /æ/ was present. Perceptual sensitivity was clearly above 0 chance ($M = 1.091$; $SD = 0.978$; Lower CI = 0.760, Upper CI= 1.422; $t(35) = 6.694$, $p < 0.0001$, $BF_{10} = 34.36$, Cohen $d = 1.116$ -large effect size-, 95% CI: Lower=0.693, Upper=1.528). We then assessed whether individual perceptual accuracy was associated with individual performance in production, the latter indexed by the Mahalanobis DS. As revealed by the analysis, there was no evidence of a positive correlation (Spearman correlation = -0.174, $p = 0.31$, $BF_{10} = 0.335$, providing moderate evidence for the null hypothesis, see Figure 4), suggesting that non-native speech sound perception and production might rely on distinct sound representations in novice learners.

Figure 4. Inter-individual correlation between accuracy in non-native vowel identification and vowel production (non-word reading), in Mahalanobis distance. [Colour figure can be viewed at wileyonlinelibrary.com]

Metacognitive performance in non-native sound identification and production

Second, we assessed participants' metacognitive performance (i.e., the ability to endorse higher confidence ratings for correct relative to incorrect responses) in both perception and production tasks. In the perception task, we used a logistic regression to examine how accuracy (0 vs 1) relates to trial-by-trial confidence ratings. As a dependent metric, we used the area under the receiver operating characteristics (ROC) curve of the logistic regression. The ROC is a sensitive, nonparametric bias-free measure of predictive performance in binary classification, with 0.5 being the theoretical chance level. The ROC

represents the ratio of the true positive rate (i.e., the regression predicts ‘correct’ given the trial is correct) against the false positive rate (i.e., the regression predicts ‘correct’ given that the trial is incorrect). This was computed separately for each participant (ROC scores ranged from 0 to 1, with 0.5 indicating chance level). Figure 5 shows the distribution of the ROC scores of the logistic regression across participants. These were significantly higher than 0.5 chance ($M = 0.604$, $SD = 0.107$, Lower CI = 0.567, Upper CI = 0.640; $t(35) = 5.79$, $p < 0.001$, $BF_{10} = 12182.7$, Cohen effect size=0.965 -large effect size-, 95% CI: Lower=0.564, Upper=1.357;) indicating that confidence ratings significantly predicted perception accuracy. Given that deviation from normality was detected in the ROC scores, we verified the result by the means of a Wilcoxon signed-rank test ($Z=644$, $p<0.001$, Cohen effect size=0.934 -large effect size-, 95% CI: Lower=0.865, Upper=0.968).

We also confirmed this result using measures of metacognitive sensitivity based on signal detection theory (i.e., meta- d')ⁱⁱⁱ. Meta- d' was also above 0 chance ($M = 0.738$; $SD = 0.943$; Lower CI = 0.42; Upper CI = 1.058; $t(35) = 4.70$, $p < 0.001$, $BF_{10}=583.6$; Cohen effect size=0.784 -medium effect size-, 95% CI: Lower=0.405, Upper=1.154). Given that a deviation from normality was detected in the meta- d' scores, we verified the result by the means of a Wilcoxon signed-rank test ($Z=579$, $p<0.001$, Cohen effect size=0.739 -medium effect size-, 95% CI: Lower=0.518, Upper=0.867).

Figure 5. Metacognitive performance in vowel identification task, indexed by the ROC scores of a logistic regression analysis relating confidence ratings to the identification accuracy. The bars represent the confidence intervals around the mean. The grey filled bar plots the mean. Dots represent individual data points.

Note that since production accuracy is a continuous response, we were not able to use the meta- d' metric to compare metacognitive performance in production and perception. To analyse metacognition in the production task, we used a linear regression model to predict the precision of the production (DS) for each participant across trials based on the trial-wise confidence ratings. Figure 6 depicts the distribution of the regression coefficients, which are low, on average, and not significantly different from zero ($M = -0.007$, $SD = 0.358$, Lower CI = -0.128 , Upper CI = 0.014 ; $t(35) = -0.115$, $p = 0.908$,

$BF_{10}=0.18$; Cohen effect size=-0.019, 95% CI: Lower=-0.346, Upper=0.308). Given that a deviation from normality was detected in the production scores, we verified the result by the means of a Wilcoxon signed-rank test ($Z=248$, $p = 0.402$, Cohen effect size=-0.16, 95% CI: Lower=-0.503, Upper=0.214).

This result indicates that participants did not display a fine-grained metacognitive insight about the quality of their production, as indicated by lack of a relationship between confidence ratings and the acoustic distance from their productions to the target native vowel. Measuring metacognition using regression models has potential drawbacks as estimations may be influenced by the confidence bias, namely, the tendency of individuals to be over- or under-confident (see Fleming & Lau, 2014), but they, however, reliably indicate whether confidence ratings track the correctness of behavioural responses (Rahnev et al., 2020). As we shall see below, individual confidence biases were similar and correlated across the perception and production tasks, suggesting that they could not account for the results of the regression analyses in metacognition that we report.

Figure 6. Metacognitive performance in non-word reading, indexed by a linear regression relating confidence ratings to production performance. The bars represent the confidence intervals around the mean. Dots represent individual data points.

In a separate post-hoc analysis, we addressed whether participants had a less refined, “binary” sense of their accuracy, in terms of the ‘nativeness’ of their production (native-like/not native-like), rather than a fine-grained continuous representation of their production accuracy. Therefore, as mentioned in the methods, we dichotomized the responses in the production task, as a function of their location within or outside of the French native vowel space, and assigned each non-native production to either of the two categories: within or outside the native zone (see Methods). However, the participants’

confidence level was not significantly different between the productions within and outside the native space (“within”: $M = 4.393$, $SD = 0.839$; “outside”: $M = 4.458$, $SD = 0.859$; Lower CI = -0.199 , Upper CI = 0.07 ; $t(35) = -0.978$, $p = 0.33$, $BF_{10}=0.279$; Cohen effect size= -0.163 , 95% CI: Lower = -0.491 , Upper = 0.167), indicating that confidence did not track participants’ accuracy in production. Given that a deviation from normality was detected in the meta-d’ scores, we verified the result by the means of a Wilcoxon signed-rank test, which revealed a similar non-significant effect ($Z = 268$, $p = 0.83$, Cohen effect size= -0.045 , 95% CI: Lower= -0.410 , Upper= 0.333).

Assessing the relationship between metacognitive ability in speech sound perception and production

We assessed, via Spearman correlation, the relationship between inter-individual variation in metacognitive sensitivity in non-native speech sound identification and production. The results did not reveal a relationship between metacognitive sensitivity in perception and production (Spearman correlation = 0.07 , $p = 0.684$, $BF_{10} = 0.24$, Figure 7). We also assessed whether participants' feeling of confidence was correlated across the two language domains, the analyses can be found in Appendix S2.

Figure 7. Absence of a relationship between metacognitive ability in vowel perception (identification) and in vowel production (non-word reading). Metacognitive sensitivity in perception was indexed by the ROC scores of the logistic regression predicting accuracy by confidence. Metacognitive sensitivity in production was indexed by the linear regression coefficient relating confidence to accuracy.

Discussion

In the current study, we developed a paradigm to investigate, for the first time in one single study and within the same participants, metacognition in non-native language (phonemic) perception and production. To do this, we familiarised L1-Spanish speakers with a novel French vowel contrast /ø/-/œ/, and then assessed their confidence in both a vowel identification and non-word reading task on a trial-by-trial basis. Our main goals

were: (1) to examine metacognition in two different but related language domains (speech sound perception and production); (2) to examine the relationship between metacognition in speech perception and production; and (3) to address the relationship between the phonemic perception and production in novice language learners. In what follows, we first discuss the results of the perception and production tasks and then the metacognitive processing in these two domains.

Perception and production of L2 speech sounds

Regarding the primary task performance, in line with previous research (Kartushina & Frauenfelder, 2014), Spanish speakers demonstrated difficulties in their perception and production of the French /ø/-/œ/ contrast. Although, overall, they identified the target vowels above chance, the perception accuracy was rather moderate (69% correct), and the average speech production distance was around 4 standard deviations from the mean of the target native (French) space, with only 32% of productions realised within the native target-vowel zone. This indicates, in line with the L2 speech perception models such as PAM (Best, 1995) and SLM (Flege, 1995), that similar non-native speech sounds having no close counterparts in the native (vowel) space, assimilate to one uncategorized novel sound and are likely to be misperceived and/or mispronounced until listeners can discern the phonetic difference between them. The results revealed considerable inter-speaker variability in the perception and production of the novel difficult non-native contrast, demonstrating, similar to previous research, the role of

individual-specific factors in L2 speech sound processing (Bradlow et al., 1997; Flege & Schmidt, 1995; Hanulíková et al., 2012; Nagle, 2018).

We found no relationship between individual accuracy in speech perception (vowel identification) and production (non-word reading) in novice learners, suggesting absence of a link between the two domains, at least when learning novel perceptually-similar L2 sounds distinct from native categories. This result is consistent with previous research, showing that, while experienced L2 speakers show a moderate-to-strong relationship between L2 perception and production (Baker & Trofimovich, 2006; Bettoni-Techio et al., 2007; Flege, 1993, 1999; Flege et al., 1997, 1999; Flege & Eefting, 1987a; Flege & Schmidt, 1995; Hattori & Iverson, 2010; Jia et al., 2006; Kluge et al., 2007; Zhang & Peng, 2017), speakers with less experience or novice learners show only weak or no relationship at all (Jia et al., 2006; Kartushina et al., 2015; Kartushina & Frauenfelder, 2014; Li et al., 2019). This may indicate that the two domains align with experience (Flege and Schmidt, 1995), as the perception-production link varies across time (Nagle & Baese-Berk, 2021) and has been shown to be stronger in experienced L2 speakers (Rallo Fabra & Romero, 2012). Yet, even experienced L2 speakers might show a dissociation between the two domains, when the tasks used to assess L2 perception and production tap into different processing levels (e.g., Hao & de Jong, 2016; Melnik-Leroy et al., 2021; Peperkamp & Bouchon, 2011). For instance, while no relationship has been reported between L2 speech perception and production at the prelexical, acoustic-phonetic level, when using acoustic measures for L2 production accuracy (Hattori & Iverson, 2010; Schertz et al., 2015), a moderate-to-strong

relationship was revealed at the phonological/lexical level, when using more global perceptual (e.g., subjective) measures of perception and production accuracy (e.g., intelligibility ratings, see Evans & Alshangiti, 2018; Flege et al., 1999; Inceoglu, 2019) or tapping into similar levels of processing (Bohn & Flege, 1997; Flege, 1993; Flege et al., 1997, 1999; Flege & Schmidt, 1995; Melnik & Peperkamp, to appear; Nagle, 2018). In the current study, we carefully controlled for input/stimuli in exposure and during the tasks (we used unfamiliar phonetic symbols “ø” or “æ” for novel non-native vowels), aiming at assessing non-native perception and production at a similar prelexical, i.e., phonemic level. We did not use a sound repetition task to avoid relying on acoustic processing only (i.e., imitation) and we used non-words to avoid lexical effects. Nevertheless, the results revealed no association between the two domains in novice learners, suggesting that either the relationship is not yet stable at the onset of phonetic learning or that it might be lagging, as suggested in recent research. Longitudinal studies assessing the development of the perception-production relationship are needed to provide further support for this hypothesis (see Nagle & Baese-Berk, 2021 for a review).

Another factor that might have contributed to the lack of a correlation between L2 sound perception and production is the use of acoustic measures to assess L2 production. In the current study, we opted for an objective acoustic analysis of non-native vowel production, instead of more subjective intelligibility ratings that typically assess overall word production, including individual segments, supra-segmental information and coarticulation, and can be subject to bias due to raters’ familiarity with the learners’

language/accent (Winke et al., 2013), raters' background and attitudes (Kang et al., 2019) and learners' fluency (Duijm et al., 2018). Although there seems to be a general relationship between acoustic (objective) and subjective measures (e.g., ratings) of L2 production (see, e.g., Flege et al., 1997; Wang et al., 2003; although see Delvaux et al., 2013 showing only partial relationship) - providing grounds for using either of them as an informative pronunciation measure - acoustic analyses provide a finer-grained (continuous) measure of accuracy. This might not be captured by a dichotomised measure of perceptual accuracy (as used in the current study), as compared to a 2-forced-choice identification task over a continuum, e.g., from the French /ø/ to /œ/. For instance, previous research in L2 learning revealed no relationship (at the prelexical level) between L2 speech perception and production, when using acoustic measures of L2 production (Bohn & Flege, 1997; Schertz et al., 2015), as compared to when using subjective measures, e.g., intelligibility ratings, that assess L2 pronunciation beyond segmental accuracy, i.e., supra-segmental, coarticulation, etc. (Evans & Alshangiti, 2018; Flege et al., 1999; Inceoglu, 2019). In contrast, a study by Hattori and Iverson (2010) showed no relationship between the production accuracy of the relevant acoustic cues and the perceptual sensitivity to these cues. These inconsistencies might be partially attributed to the type of acoustic cues used to assess L2 production. As suggested in a recent review paper (Nagle & Baese-Berk, 2021), acoustic features distinguishing L2 sounds in native speakers' speech might differ from those that L2 learners use when attempting to differentiate L2 contrasting sounds in production, hence more complex acoustic analyses, taking into account a multitude of features, might be needed to fully describe L2 pronunciation accuracy and the acoustic

features that L2 learners use to differentiate L2 contrasting sounds (e.g., linear discriminant analysis, see Mairano et al., 2019). A recent study (Song & Eckman, 2021) revealed a relationship between L2 speech perception and production when the acoustic analysis of L2 speech included the same set of cues that native L1 speakers use to distinguish the target vowel contrast (duration, F1 and F2, although using as a binary response, e.g., a cue is present vs absent), but not when the production was assessed via raters' identification, suggesting that fine-grained acoustic analyses of L2 production might be better suited to assess L2 segmental pronunciation, as compared to raters' judgements. In the current study, to assess L2 speakers' production, we used only F1 and F2, as these are the main cues that native French speakers use to contrast the two front rounded vowels. However, it is not impossible that native Spanish speakers' rounding of these vowels (revealed by the third formant, F3) differed from that implemented by native French speakers and adding this cue in the accuracy measure would have increased the strength of the perception-production relationship (see Llompart & Reinisch, 2018, for work on the role of acoustic cues in L2 perception). To examine this possibility, and the role of F3 in the production of this novel contrast, we ran a series of analyses (available on the project's OSF), that revealed: (1) no difference in F3 between Spanish and native French groups, nor interaction between group and vowel; (2) no correlation between the F3-distance to the norms (participants' F3 and native French speakers' F3) and the confidence rating, and (3) no correlation between the F3-distance to the norms and participants' identification accuracy, for either vowel. These additional analyses suggest that, similar to native speakers of French, Spanish participants did not use F3, a roundness cue, to distinguish the

two French vowels (see figure individual_f1f3_native_vs_learners.jpg displaying individual differences in the implementation of F3 on the project's OSF) and that the accuracy in F3 (alone) was not related to participants' contrast perception. Future research needs to examine fine-grained representations underlying L2 sound perception and production (across different learner profiles and tasks) via more exhaustive measures of production (for instance, over the three acoustic cues, F1, F2 and F3 to have a 3D distance metric) and perception accuracy.

Metacognition in L2 speech sound perception and production

Regarding metacognition, we observed that participants had insights into their accuracy in non-native sound perception, in that their confidence ratings were associated with their accuracy in non-native vowel identification. This result, stemming from a rich trial-by-trial analysis of participants' performance (200 trials per participant), is in line with previous L2 learning research in which self-confidence was rated according to the individuals' overall task performance. For instance, Yule et al. (1987) showed that improvements in non-native sound perception following training were accompanied by improvements in L2-learners' self-confidence. Yet, in early learners, Yule and colleagues (Yule, Damico, et al., 1987) revealed that overall improvements in L2 identification accuracy were not accompanied by improvements in self-monitoring, suggesting that, at the beginning of learning, L2 learners might be most focused on improving their identification skills and unaware of their progress. However, in contrast with the present study, Yule and colleagues did not assess the relationship between confidence and accuracy on a trial-by-

trial basis, but only self-monitoring at the beginning and at the end of training. Our results in novice learners, on the other hand, are based on a more sensitive, trial-by-trial analysis and indicate that metacognitive ability in non-native speech sound perception can be efficient from the onset of learning. Though future research is still needed, we propose, tentatively, that this metacognitive ability can guide foreign language learners' acquisition of difficult L2 sounds.

The confidence ratings in the production task, on the other hand, did not predict the quality of the production, neither when indexed by a continuous acoustic measure of distance from the participants' production to the target native space, nor when indexed by a categorical measure of nativeness in terms of the production being within or outside the "native vowel zone". These results suggest that metacognition in non-native speech sound production in novice learners is less efficient compared to metacognition in non-native speech sound perception.

Previous research, in experienced learners, that used a 'nativeness' criteria to measure L2 (segmental) production accuracy, reported robust overall estimation of L2 production abilities: participants' self-estimated pronunciation correlated strongly with the overall nativelikeness of their L2 production and, to a lesser extent, with the accuracy in the production of specific L2 sounds (Peperkamp & Bouchon, 2011). Similarly, Dłaska and Krekeler (2008) reported a moderate alignment between experienced L2 speakers' self-assessments and the raters' assessments of accuracy; however L2 speakers had difficulties in recognising a considerable number of productions being mispronounced, indicating that

metacognition in L2 speech production might still be relatively modest, even in experienced L2 speakers. When assessing broader linguistic levels (self-assessment of sentence production, discourse), L2 speakers mostly misjudge their production accuracy (Trofimovich et al., 2016) and might not be aware of their overall comprehensibility (Strachan et al., 2019), suggesting that multi-level monitoring, involving micro (e.g., sounds) and macro-linguistic structures, is a complex cognitive skill that can be beyond the reach of even experienced L2 speakers. Alternatively, better acceptability of self-produced accented speech (i.e., failure to detect mispronunciations) and better comprehension of words produced by one's own voice can be attributed to the familiarity effect, suggesting that exposure to one's own accented productions can induce adaptation, which, in turn, can hinder changes in L2 experienced speakers' pronunciation (Eger & Reinisch, 2019; Mitterer et al., 2020) and might encourage them to seek input from native (unfamiliar with the accent) speakers (Carey et al., 2011). Similar familiarity effects have been reported in native raters' assessment of L2 pronunciation, suggesting that exposure to a foreign accent might facilitate adaptation for this specific accent, but hinder the reliability of the assessment (Carey et al., 2011).

Successful L2 speech sound learning frequently involves (1) distinguishing cross-linguistic differences between native and non-native speech sounds, which supports the establishment of novel L2 categories, and (2) discerning differences between similar non-native speech sounds, which is necessary for the establishment of contrasting target-language-like sound categories used in minimal word pairs like 'ship-sheep' in English

(Flege & Bohn, 2021). In the current study, we cannot disentangle between these two processes. Presumably, those Spanish listeners who were able to correctly identify the French contrast and confidently report that, discerned the cross-linguistic differences between these French sounds and similar Spanish sounds (e.g., back rounded mid /o/ and, to a lesser extent, front unrounded mid /e/). However, it should be noted that French front rounded vowels do not systematically map into one specific Spanish category, but rather into a new category (in the SLM terms) with the two vowels assimilating to one uncategorized vowel (in the PAM-2 terms); hence, native Spanish speakers' ability to correctly assess their perception and production of the French contrast can also reflect their ability to distinguish the two non-native vowels. The results of the current study suggest that metacognition could guide L2 sound learning by providing learners with self-confidence and support in the learning process, whether that be to distinguish cross-linguistic differences between L2 and similar L1 speech sounds or between L2 speech sounds, in perception and production or both. Future research needs to address what types of L2 sound learning are facilitated by greater metacognitive awareness and how metacognition can be incorporated in current L2 learning models.

Metacognition in L2 speech sound perception and production: domain general or domain specific?

Finally, the results of the regression analyses revealed no evidence for an association between participants' metacognitive ability in speech sound perception and production. Therefore, our results do not suggest that metacognition in non-native language learners is

mediated by a domain-general system operating across the two domains of phonemic perception and production, similar to what has been suggested for other cognitive processes (see Rouault et al., 2018, for a meta-analysis in the perceptual and memory domains suggesting that both domain-general and domain-specific monitoring systems might co-exist). However, the lack of alignment between the metacognitive processing in (non-native) speech sound perception and production can also be attributed to differences in the underlying processes and/or immaturity or instability of the phonemic representations for the newly learnt non-native speech sounds.

While self-assessment of one's own production relies on a goodness of fit between the motor, somatosensory and auditory consequences of the sound pronunciation (or output) and the phonemic representation for this specific sound, or the auditory target (Guenther, 2006), self-assessment of one's own perception, on the other hand, relies on a goodness of fit between the auditory input (incoming sound) and the phonemic representation for this specific sound, the auditory target. Previous research suggests that when speaking a non-native language, L2 learners might have less efficient post-articulatory sensory monitoring (Simmonds et al., 2011) that is used to adjust and correct sound articulation, on-line, to match the auditory target (Guenther, 2006). This deficiency can disadvantage L2 learners' assessment of their own production, leading to a decrease in the quality and/or quantity of available information to assess segmental production. Production monitoring over larger linguistic units (words, sentences) might be less focused on individual sounds but rather take into account other relevant global features, as, for

example, fluency, overall accentedness, suprasegmental cues, etc., which provide richer input for the assessment. This, however, might compromise the assessment (in particular in novice learners) as multi-level monitoring is required (Trofimovich et al., 2016). Language experience can contribute to improvements in metacognitive processing, by either strengthening weak sensory monitoring (for instance, via intensive experience in L2 speech sound production, cf. Simmonds, 2015) and/or tuning the auditory targets. Additional work is needed to further tackle this issue.

Though there was no association between metacognitive ability across the two domains, individual confidence ratings were significantly correlated between the perception and production tasks. This result indicates that participants felt similarly confident and experienced a similar task difficulty related to their performance across the two language tasks (non-native sound perception and production), even though the actual metacognitive performance did not correlate across them. Importantly, the correlation between self-confidence in perception and production suggests that the lack of an association in metacognitive performance across the two tasks was not due to differences in participants' tendency to report high/low confidence. The absence of a correlation between metacognition in language perception and production is consistent with the results of a prior meta-analysis by Rouault and colleagues (2018) and indicates that metacognitive associations across different domains of perception and memory are likely to be low and highly variable across subjects. However, to the best of our knowledge, the current study is the first to address metacognition across the domains of language perception and

production and additional work is needed to make further assessment of factors that may constrain metacognitive insight across these domains, and across the domains of perception and action more broadly (e.g., paradigms jointly assessing confidence in both sensory and motor, non-linguistic signals).

Implications

The current work has an important pedagogical implication. Previous research has already shown that individuals can improve their ability to assess their own accuracy in L2 speech sound production and perception (Yule et al., 1987), yet little is known whether this ability can be trained. In light of the current results, suggesting that self-assessment (reliance of self-confidence) can successfully guide L2 learning, training individuals to become more accurate at assessing their own perception and production can lead to better learning outcomes and facilitate L2 learning. This is important as native L2 speakers' assessment of L2 speakers' production can be unstable and vary as a function of the raters' age and native language (Saito et al., 2019) and prone to social bias (Reid et al., 2019) and task effects (Crowther et al., 2018). The hypothesis that training metacognition can increase the efficiency of L2 learning is further supported by research on the use of metacognition in a classroom teaching, in a broader sense, showing that metacognitive instruction can enhance the effectiveness of corrective feedback (Sato & Loewen, 2018). Our results demonstrating a lack of efficient metacognitive skills in novice learners' production suggest that novice learners' L2 sound representations operate at a relatively coarse level, which can limit the use of these representations in a fine-grained way to tune their production at

the onset of learning. Further learning can rely more heavily on L2 teachers' feedback, which has been proven to be equally effective when teachers of L2 pronunciation are both native and non-native (Henderson et al., 2012; Levis et al., 2016). Teachers' feedback can also be used in students with low meta-cognitive skills (which might be related to anxiety, among others, cf MacIntyre et al., 1997).

In sum, the current findings suggest that L2 novice learners have an accurate 'overall/gross' estimation of their L2 phonemic skills: they accurately self-monitor outcomes in their L2 speech perception, yet the metacognitive system seems to weakly monitor the precision of L2 production, which is likely related to unstable or imprecise representations for novel non-native speech sounds. These results are encouraging and valuable for foreign-language teaching research, as they suggest that a brief auditory exposure to non-native speech sounds might suffice to guide perceptual learning and further pronunciation tuning in novice adult learners. Future research needs to address the development of metacognitive monitoring in L2 processing as a function of experience and proficiency, as recent research suggests that familiarity with the one's own accented voice leads to accent adaptation/acceptability that might prevent pronunciation improvement in L2 experienced learners (Mitterer et al., 2020).

Conclusion

To conclude, the results of the current study shed new light on the mechanisms involved in non-native speech perception and production, and the role of metacognition in L2 language processing. Previous research has already highlighted the role of individual

differences in L2 learning (Golestani & Zatorre, 2009; Inceoglu, 2019; Schertz et al., 2015) and of metacognition in L2 classroom based learning (Sato & Loewen, 2018); the current study contributes to this line of research and provides evidence that individual differences in metacognition (i.e., the ability to assess one's-own L2 perception and production) can also account for variability in L2 learning and can be used as an anchor to facilitate L2 speech sound acquisition, and potentially enhance learning outcomes when trained. We believe that future research along the lines of the current study has the potential to inform the development of novel and more accurate strategies of self-assessment during language learning, to adapt L2 learning strategies and to account for differences in metacognition in L2 models and L2 teaching.

Data availability statement

Experimental data, stimuli, experimental software and analysis scripts are available in the following OSF link: <https://bit.ly/3Dqsf2s>

Endnotes

ⁱ In order to have identical CV structure for both vowels, we asked native French speakers to pronounce the final consonant in CœC words (coeur, odeur, feur*, leur, peur) silently.

ⁱⁱ The Bayes factor (BF10) is used to quantify the level of evidence in the data for the alternative/null hypotheses. BF10 between (i) 1-3 (ii) 3-10 (iii) 10-30 (iv) 30-100 are considered (i) anecdotal (ii) moderate (iii) strong and (iv) very strong evidence for the alternative hypothesis, respectively. Inversely, BF10 between (i) 1-0.33 (ii) 0.33-0.1 (iii) 0.1- 0.03 and (iv) 0.03-0.01 are considered (i) anecdotal (ii) moderate (iii) strong and (iv) very strong evidence for the null hypothesis, respectively (Quintana & Williams, 2018).

ⁱⁱⁱ Meta-d' provides an estimation of the precision/quality of one's self-evaluation (i.e., the correlation between confidence ratings and perceptual accuracy) and that critically is independent of one's tendency to report high confidence (Maniscalco and Lau, 2012; see also Methods).

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Appendix S1. Settings for linear regression and logistic regression.

Appendix S2. Inter-subject correlations between the mean confidence ratings in the perception and production tasks