ORIGIN OF ACOUSTIC-VESTIBULAR GANGLIONIC NEUROBLASTS IN CHICK EMBRYOS AND THEIR SENSORY CONNECTIONS

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Running head: Origin and projection of otic neuroblasts

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ABSTRACT

The inner ear is a complex three-dimensional sensory structure with auditory and vestibular functions. It originates from the otic placode, which generates the sensory elements of the membranous labyrinth and all the ganglionic neuronal precursors. Neuroblast specification is the first cell differentiation event. In the chick, it takes place over a long embryonic period from the early otic cup stage to at least stage HH25. The differentiating ganglionic neurons attain a precise innervation pattern with sensory patches, a process presumably governed by a network of dendritic guidance cues which vary with the local micro-environment. In order to study the otic neurogenesis and topographically-ordered innervation pattern in birds, a quail-chick chimaeric graft technique was used in accordance with a previously determined fate-map of the otic placode. Each type of graft containing the presumptive domain of topologically-arranged placodal sensory areas was shown to generate neuroblasts. The differentiated grafted neuroblasts established dendritic contacts with a variety of sensory patches. These results strongly suggest that, rather than reverse-pathfinding, the relevant role in otic dendritic process guidance is played by long-range diffusing molecules.

INTRODUCTION

The initial morphological sign of incipient inner ear development is the formation of the otic placodes as thickened portions of the cephalic ectoderm on both sides of the developing hindbrain. These extend longitudinally from rhombomere 4 to pro-rhombomere C levels in birds (Sánchez-Guardado et al. 2014). Cell-fate specification and morphogenesis of the placode seems orchestrated by diffusible molecules released from nearby tissues and the otic epithelium itself. This signaling network leads to the differentiation at specific locations of various sensory and non-sensory patches in the developing membranous labyrinthine wall, a process that also underlies specification of the derived sensory neuroblasts which migrate a short distance away from the otic epithelium into the underlying mesenchyme to create the acoustic-vestibular ganglion (AVG) (Bok et al. 2007; Fekete and Campero 2007; Schneider-Maunoury and Pujades 2007; Whitfield and Hammond 2007; Groves and Fekete 2012; Wu and Kelley 2012; Chen and Streit 2013; Lassiter et al. 2014; Raft and Groves 2015; Alsina and Whitfield 2017).

Neuroblast specification is the first cell differentiation event occurring in the developing vertebrate inner ear (Carney and Silver 1983; Alvarez et al. 1989; Hemond and Morest 1991; Ma et al. 1998, 2000; Fariñas et al. 2001; Alsina et al. 2004, 2009; Abello and Alsina 2007) *Neurogenin1* (*neurog1*), a neural-specific basic Helix-Loop-Helix (bHLH) transcription factor, is expressed in the placodal ectoderm prior to the onset of neuroblast delamination. It is required for the differentiation of proximal cranial sensory neurons, which are completely absent in *neurog1* null mutants, for sensory neuron projections to the inner ear (Ma et al. 1998, 2000; Matei et al. 2005), and for the activation of genes as *NeuroD*, *Atoh1*and the Delta/Notch signaling pathway, which together determine an irreversible commitment of otic neurons (Ma et al. 1998; Abelló et al. 2007; Alsina et al. 2009; Yang et al. 2011; Coate and Kelley 2013; Gálvez et al. 2017). *Sox2*, *Fgf19*, and *Prox1*, among other genes, are also involved in fate specification and neurogenesis (Stone et al. 2003; Sanchez-Calderon et al. 2007; Sánchez-Calderón et al. 2007a,b; Alsina et al. 2009; Puligilla et al. 2010; Wu and Kelley 2012; Dvorakova et al. 2016; Gálvez et al. 2017).

The subsequent dendritic ganglionic innervation of hair cells of developing sensory patches is carried out by ganglionic neurons (Kawamoto et al. 2003; Fritzsch 2003; Beisel et al. 2005; Fekete and Campero 2007; Fritzsch et al. 2015; Delacroix and Malgrange 2015; Zhang and Coate 2017). These neurons ultimately project their axons to the segmentally-organized acoustic and vestibular sensory nuclei of the hindbrain (Fritzsch et al. 2002; Maklad and Fritzsch 2003; Maklad et al. 2010; Mahmoud et al. 2013; Straka and Baker 2013; Elliott and Fritzsch 2018; see also refs. therein). Despite the abundance of descriptive and experimental studies on the specification of areas of neurogenesis (Liu et al. 2000; Rubel and Fritzsch 2002; Stone et al. 2003; Sanchez-Calderon et al. 2007a; Koundakjian et al. 2007; Alsina et al. 2009; Dyballa et al. 2017) and the subsequent orderly dendritic connection (Rubel and Fritzsch 2002; Fekete and Campero 2007; Holt et al. 2011; Simmons et al. 2011; Coate and Kelley 2013; Mao et al. 2014; Lassiter et al. 2014; Raft and Groves 2015; Coate et al. 2015; Meas et al. 2018), some aspects of the molecular and cellular mechanisms involved still call for further investigation to better understand these developmental events.

It has been suggested that the complex ordered innervation of the diverse acoustic and vestibular sensory epithelia by maturing ganglionic neurons may be governed by a code of dendritic guidance cues acting at key decision points (Rubel and Fritzsch 2002; Fritzsch 2003; Fekete and Campero 2007). Several specific hypotheses have been proposed to explain the mechanisms guiding the leading processes of apparently mixed populations of differentiating neuroblasts towards specific sensory epithelia in the developing otic rudiment. A “reverse-pathfinding” mechanism was suggested by which, as ganglionic neuroblasts migrate out of the placode, each subset of neuroblasts would define the future substrate pathway for its dendrites, leaving a molecular trail to the sensory patch. The pioneering dendrites of these neuroblasts would just follow these paths backwards, thus creating topographically ordered innervation patterns which are precise with respect to specific sensory targets (Carney and Silver 1983). This assumption necessarily implies that all developing sensory epithelia generate their own neuroblasts, and predicts a clonal relationship between subgroups of ganglionic neurons and their sensory targets. However, it was later noted that some neuroblasts do not delaminate from the same site of the developing otic epithelium which they will later innervate (Noden and van de Water, 1986). The first neuroblasts are known to emerge from the anteromedial half of the otic primordium (Carney and Silver 1983; Alsina et al. 2004, 2009; Bell et al.

2008). Furthermore, the area from which all *neurotrophin*/*NeuroD*-positive ganglionic neuroblasts delaminate corresponds exclusively to the presumptive domains of the utricular and saccular maculae (Raft et al. 2007). Accordingly, the rest of the developing sensory patches would not generate any migrating neuroblasts, thus reducing the heuristic weight of the reverse-pathfinding hypothesis. Nevertheless, studies using proneuronal gene promoters and innovative labeling approaches have suggested that additional sites of neuronal specification gradually emerge within the developing otic epithelium, with otic neuroblasts eventually delaminating from all of them. In the mammalian developing inner ear, there have been direct demonstrations of delaminating neuroblasts coming from specific areas, rather than uniformly, along the growing cochlear duct (Fariñas et al. 2001; Matei et al. 2005; Yang et al. 2011). One may conclude from these results that at least the developing utricle, saccule, and cochlear duct generate neuroblasts. Consequently, the hypothesis suggests itself that genetically differentiated neurons are generated which potentially carry differential molecular profiles.

In addition to this line of thought, some other studies instead suggest the hypothesis that the sensory epithelial patches might release specific chemoattractant molecules which attract the growth cones of subsets of AVG neurons during the dendritic guidance period (Hemond and Morest 1991, 1992; Bermingham et al. 1999; Stevens et al. 2003; Fritzsch et al. 2004). Nevertheless, the particular molecular mechanisms involved in the accurate innervation pattern of sensory patches by differentiated neurons remains an open question (Rubel and Fritzsch 2002; Xiang et al. 2003; Pauley et al. 2003; Fritzsch et al. 2005; Fekete and Campero 2007).

With the intention of exploring this long-standing issue, we performed an experimental study using the quail/chick chimaeric graft method. With the experience accruing from our previous fate mapping study (Sánchez-Guardado et al. 2014), we transplanted small portions of the otic placode containing the presumptive territory of specific sensory patches, conjointly with small portions of nearby prospective non-sensory epithelium, in which ganglionic neurons may arise. (We shall refer to such mixed grafts as "expanded presumptive sensory areas"). Then, we analysed the pattern of QCPN-positive grafted ganglionic neuroblasts and were able to conclude that all grafted expanded sensory areas generate neuroblasts. By means of QN-immunoreactive labeling of the processes of graft-derived quail ganglionic neurons (Tanaka et al. 1990), we were able to determine the

patterns of their connections with sensory-area-derived receptor patches. From this analysis, we shall conclude that ganglionic neuroblasts originating from grafted small expanded presumptive sensory areas of the chick otic placode in the period analysed (HH10-HH36) do not project to the correlative grafted sensory area exclusively, but also innervate many other topologically distant sites. The data are thus more consistent with the conjecture of a diversity of long-range diffusible signals than with the simple "reverse-pathfinding" mechanism.

MATERIALS AND METHODS

Tissue processing

Fertilized White Leghorn chick (*Gallus gallus*) and Japanese quail (*Coturnix coturnix japonica*) eggs were incubated in a humidified atmosphere at 38±1°C. Avian chimaeric embryos were fixed and processed for cryostat sections as previously described (Sánchez-Guardado et al. 2009).

Grafting experiments

Chick and quail embryos were used to obtain chimaeras by exchanging specific portions of the cephalic ectoderm adjacent to the hindbrain at the 10-somite stage (HH10, (Hamburger and Hamilton 1992)) in unilateral homotopic and isochronic transplants. Six types of transplants were carried out (Figure 1a, b). These grafting experiments were planned in accordance with the recent fate mapping study of the chick otic placode (Sánchez-Guardado et al. 2014). The constrictions between neighbouring hindbrain rhombomeres or pro-rhombomeres served as positional landmarks (see (Vaage 1969)). A grid inserted into one ocular of the operating microscope helped to identify the relative position of the presumptive domain of each sensory and non-sensory element of the avian inner ear according to either the anterior-posterior or mediolateral axes of the otic placode at the 10-somite stage. To prevent any contribution of the hindbrain and neural crest to the inner ear (D'Amico-Martel and Noden 1983; Freyer et al. 2011), the grafted territories were exclusively restricted to a small portion of the otic placode (Fig. 1c). The in ovo micro-surgical procedure was that described in detail by (Alvarado-Mallart and Sotelo 1984). Chick embryos (always the hosts) were operated on in ovo. For these in ovo operations, a small window was made in the shell. Black ink diluted in phosphate buffer was then injected into the yoke under the embryo to improve the latter's visualization. Quail embryos were always used as donors. They were excised and removed from the eggs using fine scissors, then put into phosphate buffer and pinned onto black wax. A cavity was prepared in the chick otic placode to receive the quail graft. For this purpose, the constrictions between rhombomeres and the grid inserted into one ocular helped us very precisely create the appropriate cavity using custom hand-made micro-scalpels – stainless steel needles with a thickness of 0.1-0.2 mm glued to a toothpick. The graft was prepared in parallel by excising the same area of the quail otic placode. It was then transported in a glass micro-pipette for placement into the corresponding cavity of the

host. Particular care was taken for the sizes of the cavity and the graft in the otic placode to be closely matched for the successful integration of the transplant. In particular, chimaeric embryos with different sizes of cavity and graft were discarded. After transplantation, the host eggs were closed with parafilm, sealed with paraffin, and kept at 38±1°C. The resulting chimaeric embryos were analysed at 10 days of incubation (stage HH36) when major morphogenetic changes have already taken place and all sensory elements are completely innervated (Sánchez-Guardado et al. 2013). About 180 chimaeric embryos were analysed. Any experimental embryos with a quail graft different from that which was planned or containing structures outside the otic placode, such as portions of the very close cranial placodes, were discarded. The number of grafts performed in each experiment is indicated in the corresponding sections of Results and Figure Legends.

Immunohistochemical staining procedure

QCPN (DSHB; 1/100) and QN mAb (1/10, a kind gift from Dr Tanaka) antibodies were used to visualize the bodies and processes of grafted cells, respectively. For this visualization, sheep anti-mouse (1/100; Jackson ImmunoResearch) and mouse-PAP (1/200; Jackson ImmunoResearch) antibodies were used. Histochemical detection of peroxidase activity was carried out using 0.03% DAB with 0.6% nickel ammonium sulfate and 0.005% H_2O_2.

Imaging and quantification

All preparations were photographed with a Zeiss Axiophot microscope equipped with a Zeiss AxioCam camera (Carl Zeiss, Oberkochen, Germany) and AxioVision 2.0.5.3. software, and the images were saved in 4-MB TIFF format. These were size-adjusted, cropped, contrast enhanced, and annotated with Adobe Photoshop version 7.0 software (Adobe Systems, San Jose, CA). A quantitative study was performed with NIS Elements Imaging software. The percentage of the area of each mature sensory patch innervated by grafted neurons with respect to its whole area was calculated in the six experimental types. Three qualitative groups were considered to indicate the relative amount of innervation. “Few” QN-stained axons detected in a sensory element corresponds to an innervated area of 1-33% and represented with one asterisk. “Moderate” QN-positive dendrites corresponds to 34-66% and illustrated with two asterisks. “Many” QN-stained dendrites corresponds to 67-100% and shown with three asterisks. Three, two, and one asterisks

correspond to thick, intermediate, and thin arrows, respectively, which were shown in separate figures for each grafted region (Figs. 4l, 5m, 6l, 7m, 8m, and 9g). When less than three QN-stained axons were detected within a sensory patch, a thin broken line is used (Fig. 9g). The Table 1 is a synthesis of the results for all the chimaeric embryos analysed, covering from Type 1 to Type 6 experiments, including a quantitative study concerning the arithmetic mean and the standard deviation.

RESULTS

A crucial issue in vertebrate inner ear development is the precise correlation between the topographic origin of ganglionic neuroblasts and their respective later projections to particular sensory patches in the developing membranous labyrinth. To better understand this developmental question, we performed homotopic quail-chick grafts of small portions of the otic placode which included the presumptive territory of given otic sensory areas according to a precise fate map that we had made previously for the 10-somite stage (HH10, (Sánchez-Guardado et al. 2014); Fig. 1a, b). Since vestibular and auditory ganglionic neurons might be clonally related to non-sensory epithelia (see the Discussion below), the quail grafts included a small portion of the non-sensory epithelium lying around the sensory patches considered (Fig. 1b, c). For this reason, we term the grafted tissue, comprising sensory plus adjacent non-sensory epithelium, an "expanded presumptive sensory area". The resulting chimaeric embryos were analysed in horizontal sections at 10 days of incubation (HH36) when the otic innervation pattern has been completely established (Fritzsch 1993; Sánchez-Guardado et al. 2013). This kind of experiment allows one to consider all the neuroblasts generated in a specific grafted area from the time of the transplantation (the otic placode stage, HH10) to the moment when the chimaeric embryos were fixed (HH36). However, this kind of experiment is not suited to determining whether there exists a common progenitor for hair cells and neuroblasts in each sensory patch. In particular, it was left unclear whether, when the grafts generate neuroblasts, the grafted areas were exclusively neurogenic domains or already specified sensory patches. QCPN monoclonal antibody was used to visualize the grafted quail cells in the chick otic epithelium (Sánchez-Guardado et al. 2014). QN monoclonal antibody was used to establish the innervation pattern created by graft-derived neurons (Tanaka et al. 1990).

Type 1-6 expanded placodal grafts generated neuroblasts

In order to determine whether the grafted area of each type of experiment could generate otic neuroblasts, we first analysed the existence of QCPN-stained grafted quail neurons in horizontal sections through the vestibular ganglia (VG; Fig. 2) and acoustic ganglia (AG; Fig. 3) in all chick/quail chimaeric embryos. They all clearly showed QCPN-stained neurons in the VG (arrows in Fig. 2a-f). QCPN-positive neurons were also generally

detected in the AG (arrows in Fig. 3a-e) except in Type 6 experimental embryos, whose AG was completely devoid of QCPN-stained neurons (Fig. 3f).

Neuroblasts derived from the expanded macula utriculi area innervate every sensory patch

When the presumptive placodal territory of the macula utriculi area was included in the stage-HH10 expanded graft (Type 1; mu in Fig. 4a), and the host was immunoreacted with QCPN at stage HH36 to identify the grafted area (Fig. 4b; see S1 Fig.), the graft-derived neuroblasts generated a large number of QN-stained dendrites (Fig. 4c-k). The entire extent of the grafted macula utriculi was innervated by many QN-positive fibres (Fig. 4f). The nearby macula sacculi also showed abundant quail QN-stained dendrites (Fig. 4g). Surprisingly, all ampullary cristae were innervated by fewer QN-positive fibres (Fig. 4c-e, h). The macula neglecta, located close to the posterior crista, also displayed immunoreactive fibres originating from the grafted neurons (Fig. 4h). We analysed as well the innervation pattern of the basilar papilla and the macula lagena in the cochlear duct (Fig. 4i-k). The dorsoventrally arranged basilar papilla showed many QN-stained processes over its entire extent, including its proximal (*p*-bp, Fig. 4i) and distal (*d*-pb, Fig. 4j) portions. Some areas of the distal basilar papilla were devoid of QN-positive axons (Fig. 4j'). The macula lagena, located at the end of the cochlear duct, was innervated by far fewer QN-positive dendrites (Fig. 4k). Figure 4l summarizes these results. The size of the arrows represents the relative quantity of QN-positive fibres reaching each sensory element (see also Table 1).

Neuroblasts derived from the expanded macula sacculi area

When the territory of the presumptive macula sacculi area was transplanted (Type 2; ms in Fig. 5a, stage HH10), and the host was examined by QCPN immunoreaction (between arrowheads in Fig. 5b; see S2 Fig.), the QN-positive dendritic processes of graft-derived neurons were also found to reach all sensory patches. All ampullary cristae received QN-stained fibres (ac, lc, and pc in Fig. 5c-e, h). There were clearly more of these fibres than when the expanded domain of the presumptive macula utriculi was grafted (Type 1; Fig. 4c-e, h). All maculae, including the macula neglecta and macula lagena, likewise presented many quail-derived dendritic processes (mu, Fig. 5f; ms, Fig. 5g; mn, Fig. 5h; ml, Fig. 5l). The macula lagena showed more QN-stained fibres in Type 2 than in Type 1 grafts (compare Fig. 4k and Fig. 5l). With respect to the basilar papilla, its distal portion

also displayed abundant QN-positive fibres, but less dendrites than Type1 graft (*d*-bp, Fig. 5k). Its intermediate portion showed a few QN-stained processes in its anterior part (*i*-bp, Fig. 5j), whereas its proximal portion was completely devoid of labeled cell processes (*p*-bp, Fig. 5i). The innervation patterns in the basilar papilla were clearly different in Type 1 and Type 2 experiments (compare Fig. 4i, j with Fig. 5i-k). Figure 5m summarizes these results (see also Table 1).

Neuroblasts derived from the expanded basilar papilla area

When the expanded basilar papilla area was transplanted (Type 3; bp in Fig. 6a), the QCPN-stained grafts included proximal and distal portions of this sensory area (*p*-bp and *d*-bp; between arrowheads in Fig. 6b; see S3 Fig.). Quail neurons derived from this grafted expanded sensory area also innervated all otic sensory patches, although the number of QN-labeled fibres varied among those patches (Fig. 6c-k). With regard to the ampullary cristae, the lateral and posterior cristae showed a substantial number of QN-positive fibres (lc and pc, Fig. 6d, e, h), whereas the anterior crista showed just a few QN-stained processes (Fig. 6c, c'). All maculae displayed abundant QN-labeled processes (mu, ms, mn, and ml in Fig. 6f-h, k). The basilar papilla (Fig. 6i, j) presented many QN-positive dendrites, restricted mainly to its distal portion (*d*-bp, Fig. 6j), whereas its intermediate portion received far fewer labeled innervations in its posterior part (*i*-bp, arrowhead in Fig. 6i, i'). The proximal basilar papilla was entirely devoid of QN-stained fibres (not shown). Figure 6l summarizes these results (see also Table 1).

Neuroblasts derived from the expanded macula lagena and macula neglecta areas

The Type 4 graft included the presumptive areas of both the macula lagena and the neighbouring macula neglecta (Fig. 7a, Sánchez-Guardado et al., 2014; between arrowheads in Fig. 7b, c; see S4 Fig.). In these grafts, derived quail neurons also projected to all sensory patches (Fig. 7d-l), with local differences being detected in the quantity of QN-positive processes. The posterior ampullary crista was profusely innervated (Fig. 7f, i), whereas the anterior and lateral cristae received just a few QN-stained processes (Fig. 7d, d', e). With regard to the maculae, those of the utricle and saccule were innervated by far fewer graft-derived fibres (mu and ms in Fig. 7g, h) than the maculae neglecta and lagena (mn and ml in Fig. 7i, l). In the basilar papilla, only its distal part was innervated by QN-positive dendrites (compare *d*-bp in Fig. 7k and *i*-bp in Fig. 7j). However, some

areas of the distal basilar papilla were devoid of QN-positive axons (Fig. 7k'). Figure 7m summarizes these results (see also Table 1).

Neuroblasts derived from the expanded anterior/lateral area

The fate-mapped domains of the presumptive anterior and lateral ampullary cristae are located at the rostroventral end of the embryonic otic placode (Sánchez-Guardado et al. 2014). Their joint presumptive area was included in one graft experiment type (Type 5; ac and lc in Fig. 8a). In this kind of chimaeric embryo (grafted area between arrowheads in Fig. 8b, c; see S5 Fig.), dendrites of graft-derived neurons abundantly innervated the anterior crista (ac, Fig. 8d), but fewer QN-positive dendrites were observed in the lateral and posterior cristae (more dendrites reached the lateral crista than the posterior crista; lc and pc in Fig. 8e, e', f, i). In addition, quail dendrites were observed in the macula utriculi (mu, Fig. 8g) and the macula sacculi (ms, Fig. 8h), while there were few innervating the macula neglecta (mn, Fig. 8i) and macula lagena (ml, Fig. 8l, l'). Interestingly, only the intermediate and distal portions of the basilar papilla presented quail-derived dendrites (*p*-bp, not shown; *i*-bp, Fig. 8j; *d*-bp, Fig. 8k). This innervation was particularly evident in the distal portion (*d*-bp; Fig. 8k). Figure 8m summarizes these results (see also Table 1).

Neuroblasts derived from the expanded posterior crista area

Finally, the area of the presumptive posterior crista was selectively transplanted at stage HH10 (Type 6; pc in Fig. 9a and between arrowheads in Fig. 9b; see S6 Fig.). QN-positive processes were detected in the anterior crista (ac, Fig. 9c). Quail-derived neurons also innervated the posterior crista (pc, Fig. 9d). However, very few QN-positive dendrites, in some cases just one or two, were observed in the lateral crista (lc, Fig. 9e, e') and macula sacculi (ms, Fig. 9f, f'). The other otic sensory patches were totally devoid of QN-stained fibres (not shown). Figure 9g summarizes these results (see also Table 1).

Table 1 is a synthesis of the results for all the chimaeric embryos analysed, covering from Type 1 to Type 6 experiments, including a quantitative study of the area of each sensory element innervate by grafted neurons in type of experiment. Three, two, and one asterisks correspond to thick, intermediate, and thin arrows, respectively, which were shown in separate figures for each grafted region (Figs. 4l, 5m, 6l, 7m, 8m, and 9g). When less than

three QN-stained axons were detected within a sensory patch, a thin broken line is used (Fig. 9g).

DISCUSSION

Neurogenesis at otic placode/cup stages

Otic neuroblast specification is the first cell differentiation to take place in the developing inner ear (Adam et al. 1998; Alsina et al. 2003, 2004, 2009; Abello and Alsina 2007; Bell et al. 2008; Vázquez-Echeverría et al. 2008; Wu and Kelley 2012; Lassiter et al. 2014; Raft and Groves 2015; see Introduction). *Fgf10* expression was observed in the anteromedialmost portion of the otic placode (stage HH10) and the early otic cup (stages 11-12), anticipating the pan-sensory competent territory (Alsina et al. 2004). In the chick, analysis of neural determination markers has shown a direct relationship between this pan-sensory *Fgf10*-expressing domain and otic neurogenesis (Alsina et al. 2004, 2009; Abelló et al. 2007; Bell et al. 2008). Although a different dynamic expression pattern of the *Fgf10* gene has been reported in the developing otic epithelium of mouse embryos, probably a reflection of different mechanisms of otic patch specification among vertebrate species, *Fgf10* expression is also clearly detected in the delaminating neuroblasts of the forming mammalian acoustic-vestibular ganglion (Pauley et al. 2003). It is generally accepted that *Neurogenin-1* (*Neurog1*) is an excellent otic neuronal determination gene (Ma et al. 1998, 2000). It belongs to an ancient family of basic Helix-Loop-Helix (bHLH) genes which are directly involved in cell fate determination across diverse phyla and neural systems (Alsina et al. 2009; Fritzsch et al. 2010). *Neurog1* expression is also confined to the anterior half of the otic cup (Alsina et al. 2004; Vázquez-Echeverría et al. 2008), within the *Fgf10*-expressing domain (Alsina et al. 2004) in an area probably corresponding to the future utricular and saccular maculae and likely including some ampullary cristae (Bell et al. 2008; Sánchez-Guardado et al. 2014). In addition, *NeuroD* and *NeuroM* are related bHLH transcription factors controlled by *Neurog1* (Ma et al. 1998). They are involved in the differentiation of pre-specified neuroblasts into mature neurons, as well as in neuronal migration and survival (Fritzsch et al. 2006; Alsina et al. 2009; Jahan et al. 2010). *NeuroD* and *NeuroM* expression is first detected in a few cells of the anterolateralmost portion of the early otic cup (HH12), and extends towards the anteromedial portion somewhat later (HH13) (Alsina et al. 2004; Abelló et al. 2007; Bell et al. 2008; Vázquez-Echeverría et al. 2008), with *NeuroD1* being essential for neuroblast delamination (Liu et al. 2000). Interestingly, *NeuroD* and *NeuroM* expression is detected in the entire *Fgf10*-expressing domain of the developing chick inner ear, albeit reaching the extreme posteromedial portion of the otic cup at a later stage (HH14) (Alsina et al.

2004). This is the site where the caudal sensory patches develop (Sánchez-Guardado et al. 2014). In the mouse, neurogenic events begin at the anteroposterior midline of the invaginating otic placode (Raft et al. 2004; Raft and Groves 2015). These descriptive studies, our previous fate-mapping study (Sánchez-Guardado et al. 2014), and the present work grafting different small areas carrying distinct sensory elements of the avian otic placode make it conceivable that, apart from the utricle and saccule, other portions of the developing membranous labyrinth in which the presumptive domain of some sensory patches develops participate in otic neurogenesis.

Neurogenesis at the otic vesicle stage

The origin of all otic neuroblasts has been ascribed to the anteroventral wall of the otic vesicle (D'Amico-Martel 1982; Carney and Silver 1983; Alvarez et al. 1989), with this neurogenic area being defined by the expression of such markers as *Neurog1*, *Delta1*, *LFng*, and *NeuroD* (Begbie et al. 2002; Matei et al. 2005; Raft et al. 2007; Koundakjian et al. 2007; Vázquez-Echeverría et al. 2008; Alsina et al. 2009; Puligilla et al. 2010; Radosevic et al. 2011; Wu and Kelley 2012; Sapède et al. 2012; Groves et al. 2013). Clonal fate-mapping studies of the developing chick inner ear using a replication-defective retrovirus have shown AVG neurons and sensory cells in the utricular macula to share a common lineage (Satoh and Fekete 2005), and genetic fate-mapping of the *Neurog1*-expressing cells in the mouse inner ear has provided evidence for a shared lineage of AVG neurons and the utricular and saccular maculae (Raft et al. 2007; Raft and Groves 2015). Koundakjian and co-workers (Koundakjian et al. 2007) have shown that early *Neurog1*-expressing cells give rise mainly to the vestibular ganglion, whereas the late *Neurog1*-expressing cells contribute to the cochlear ganglion (Koundakjian et al. 2007). Temporal coupling of the vestibular/acoustic neuronal and utricular/saccular macular fate specifications has been hypothesized (Deng and Wu 2016). However, the possibility of other areas participating in the generation of additional neuroblasts can not be excluded. Interestingly, neurosensory lineage reconstruction by imaging zebrafish embryos in vivo has clearly shown the posterior expansion over time of the neuroblast delamination domain (Dyballa et al. 2017). Also in zebrafish embryos, in the posteromedial portion of the otic epithelium there is a population of bipotent progenitors that generate sensory cells and neurons, and in these progenitors *neurog1* prevents *atoh1* expression, whereas *neurod1* is directly involved in hair-cell fate specification (Sapède et al. 2012).

Islet1-positive neuroblasts delaminate from the ventral pole of the chick otic vesicle (Alsina et al. 2004; Raft et al. 2004; Li et al. 2004; Radde-Gallwitz et al. 2004). In this respect, it is well accepted that at least the auditory sensory organ and corresponding ganglion neurons develop from this ventral area (Radde-Gallwitz et al. 2004; Raft and Groves 2015). Furthermore, the transcription factor *Prox1* is implicated in sensory and neural cell fates in the chick inner ear (Stone et al. 2003). Although delamination of *cProx1* positive cells from the dense *cProx1* expressing domain is not easily observed, *cProx1* expression is clearly detected at the medial edge of the anterior dense region at stage 21 (Stone et al. 2003), probably corresponding to a small non-sensory domain located between the anterior/lateral cristae and the macula utriculi. Interestingly, scattered *Prox1*-/Tuj1(βIII-tubuline)-positive cells are found within a continuous anteroventral-to-posteromedial band of the otic sensory anlagen, and they clearly migrate into the AVG primordium at the otocyst stage (Stone et al. 2003). In addition, analysis of *Fgf19* expression has also shown a possible delamination of otic neuroblasts far from the anteroventral portion of the otic vesicle, in an area corresponding to the presumptive territory of the posterior crista (Sánchez-Calderón et al. 2007a). The analyse of all the expanded sensory elements in early stages performed in this work and these previous findings clearly suggest the existence of distinct neurogenic areas in the developing inner ear, beyond the more precocious presumptive anteroventral territories Koundakjian et al. 2007, Raft et al. 2007, Liu et al. 2000, Fariñas et al. 2001; Yang et al. 2011, Satoh and Fekete 2005).

Otic neurogenesis study in the developing avian inner ear using the quail/chick chimaeric graft method

In sum, various pieces of evidence point to multiple sites of delamination of otic neuroblasts from the developing membranous labyrinth over an extended period of time (from the early otic cup stage onwards). These studies confirm that otic neurogenesis takes place intensely within an anteroventral part of the pan-sensory domain, in particular the presumptive territories of the utricular and saccular maculae (Satoh and Fekete 2005; Raft et al. 2007; Raft and Groves 2015). They lend powerful support to the assumption that neurogenesis also occurs within the auditory organ (Fariñas et al. 2001; Yang et al. 2011). However, there has yet to be full verification of the conjectured existence of

multiple sites of otic neurogenesis within the developing membranous labyrinth, in particular, the presumptive territories of the cristae and the rest of the maculae in birds, and certainly in some adjacent non-sensory domains. Our results contribute to shedding light on this question, although the grafting experiments do not allow determinate the neuroblasts generation time or their clonal relationship with hair cells from the sensory patch where they delaminated. We have analysed experimentally the origin of neuroblasts from diverse fate-mapped sites of the avian otic epithelium. When small portions of the otic placode containing the presumptive territory of sensory patches plus contiguous non-sensory epithelium were grafted homotopically (Sánchez-Guardado et al. 2014), the resulting chimaeric embryos showed that all the developing expanded sensory areas generate QCPN-positive neuroblast populations (Table 1). Two possible explanations could be considered: (1) all grafted areas contain small portions of the previously described neurogenic domain at stage HH10, and neuroblasts are generated early before sensory commitment is established; and/or (2) the grafted territory, containing the presumptive territory of sensory patches plus their contiguous non-sensory epithelium, activates neurogenesis at later points in development than those considered in previous work, thus leading to some subpopulations of otic neuroblasts being missed in the studies. The present results fit well with a previous DiI/DiO fate map study (Bell et al. 2008).

At the otic vesicle stage, it is also well known that otic neurogenesis occurs within a large sensory-competent domain of the otic rudiment defined by the overlapping expression of such pan-sensory markers as *Fgf10, Serrate1,* and *Sox2* (Raft and Groves 2015). In chick embryos, *Fgf10* transcripts are present initially in a narrow ventromedial band of the otocyst, extending from its rostral to its caudal poles (Alsina et al. 2004; Sánchez-Guardado et al. 2013). Studies of the expression pattern of Islet1, a LIM-HD protein, and *Fgf19* suggest that relevant otic neurogenesis occurs at the interface between the *Fgf10*-positive pan-sensory and the *Fgf10*-negative non-sensory domains (Alsina et al. 2004; Sanchez-Calderon et al. 2007), suggesting that compartmentalization of the developing membranous labyrinth could be involved in otic neurogenesis (Fekete and Wu 2002; Alsina et al. 2004, 2009; Raft and Groves 2015). The grafted areas analysed in this work could contain part of the narrow neurogenic band overlapping the pan-sensory *Fgf10*-expressing domain and the non-sensory domains at the otic vesicle stage. As development proceeds, the *Fgf10*-expressing area observed in the otic vesicle splits repeatedly into several separate sub-areas, creating six of the eight sensory organs present in birds. Only

the lateral crista and the macula neglecta are initially *Fgf10* negative, although they activate *Fgf10* expression after their specification as sensory elements (Sánchez-Guardado et al. 2013). The grafts performed in the present work contain one, or in some cases two, of these specified *Fgf10*-positive sensory patches plus contiguous areas of their respective non-sensory epithelia, together termed here "expanded presumptive sensory areas". It was not possible to determine whether grafted neuroblasts arose exclusively from either the sensory patch or the nearby non-sensory grafted area, or even from the interface between them. Further work would seem to be required to resolve this question.

Sensorial innervation pattern study in the developing avian inner ear using the quail/chick chimaeric graft method

Using a QN immunoreaction, which allows us to visualize the quail ganglionic dendrites approaching the quail or chicken otic sensory patches, we determined the sensory connection patterns generated by diverse graft-derived neurons. With respect to the macular areas, our study clearly showed that the expanded macula utriculi area, which contains the topologically rostralmost macula, generated many neuroblasts, and that their dendrites reached every sensory patch (Type 1 graft). The macula sacculi area, fate-mapped just caudal to the macula utriculi in the chicken otic placode, also generated many neuroblasts with indiscriminate connections (Type 2 graft). Interestingly, expanded grafts including the presumptive basilar papilla area (Type 3 graft), located even more caudally in the placode, produced fewer neuroblast, although still an appreciable number of them. In these last two types of graft (Types 2 and 3), the proximal portion of the basilar papilla was the only sensory domain devoid of QN-grafted dendrites. It is the first time reported that the caudalmost macular area, the macula lagena and the macula neglecta, also generated neuroblasts when they were grafted (Type 4 graft). There were fewer of these Type 4 derived neuroblasts than those deriving from the basilar papillary area, and hence also far fewer than those from the utricular and saccular macular areas. Interestingly, quail neuron processes from Type 4 grafted neuroblasts still innervated, although to a lesser extent, all sensory patches.

A curious finding was that the proximal and intermediate portions of the basilar papilla never received dendritic contacts from the lagenar and neglecta macular grafted areas. A pattern of gradually emerging tonotopic projection to the basilar papilla was discernible, with the rostralmost macular area (mu) differentiating earlier during development, and

first projecting to the whole basilar papilla and the other more caudal macular areas (ms, ml, and mn), differentiating later, and finally projecting exclusively to the caudalmost portion. These differences in the innervation pattern could also be related to the apex-base gradient of cellular differentiation and the innervation pattern of the developing organ of Corti (Xiang et al. 2003; Matei et al. 2005; Nichols et al. 2008; Yang et al. 2011; Wu and Kelley 2012; Kersigo and Fritzsch 2015; Dvorakova et al. 2016; Liu et al. 2016), as well as to the final tonotopic projections that connect a given position of the auditory sensory organ with the cochlear nuclei in the hindbrain (Rubel and Fritzsch 2002).

Regarding the crista-related areas, whose primordia are also aligned along the AP dimension of the placode, the anterior and lateral cases (Type 5 graft) clearly generated ganglionic neuroblasts that likewise innervated all otic sensory elements, except apparently the proximal portion of the basilar papilla. The expanded posterior crista area (Type 6 graft) generated comparatively fewer neuroblasts, which mainly innervated the anterior and posterior cristae and, to a far lesser extent, the lateral crista and the macula sacculi. The analysis of QN-positive processes of the neuroblasts from the expanded crista-related placodal areas is thus indicative of a differential connection of the dendrites from rostral versus caudal neuroblasts to the basilar papilla, as well as to other sensory patches.

In conclusion, our results have shown that: (1) neuroblasts from a small grafted area of the chick otic placode never exclusively connect with the correlative grafted sensory patch, but also with various other topologically distant areas; (2) the assumption that innervation of the developing inner ear is determined by lineage relationships between locally-derived neurons and sensory cells clearly appears to be questionable. and (3) Although each expanded presumptive sensory area can generate neuroblasts, the "reverse-pathfinding" mechanism by which pioneering dendritic processes return specifically to given sensory organs following the original migratory paths of the neuroblast ought to be completely discarded from further consideration as a realistic description of otic dendritic guidance. The focus of more advanced studies should address the possible existence of a non-specific general chemoattractant for ganglionic dendrites that is released by all sensory patches, probably in a rostrocaudal spatiotemporal sequence. One has to assume that the indiscriminate primary innervation pattern that has been demonstrated here will undergo processes of correction at later stages, eliminating

redundant connections, and finally establishing the highly selective innervation pattern described in adult animals (Echteler 1992; Delacroix and Malgrange 2015). There are various plausible factors that may lead to such significant synaptic refining. They include dilution of the efficiency of the postulated generic attractant as the size of the labyrinth grows, the possible later production of more selective attractants as the sensory patches differentiate, competition among redundant contacts and application of "the first to arrive takes all" rule, receive sensory input and trophic effects due to functional mismatch in the axonal projections of the ganglionic neurons into the corresponding hindbrain sensory columns.

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COMPETING INTERESTS

The authors declare they have no competing financial interests.

AUTHOR CONTRIBUTIONS

M.H.-S., L.-O.S.-G., and L.P. designed experiments. L.-O.S.-G. and M.H.-S. performed experiments. M.H.-S., L.-O.S.-G., and L.P. analysed data and wrote the manuscript.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest: The authors declare that they have no conflict of interest.

Ethical approval: All procedures performed in studies involving animals were in accordance with the ethical standards of the institution or practice at which the studies were conducted.

Informed consent: Informed consent was obtained from all individual participants included in the study.

FIGURE LEGENDS

Figure 1. Schematic representation of quail-chick grafting experiments at the 10-somite stage. (**a**) Schematic dorsal view of an avian embryo showing the otic placode in the cephalic ectoderm, facing rhombomeres (rh) rh4, rh5, and a large part of rhC which will soon after be subdivided into rh6 and rh7 (see (Vaage 1969)). (**b**) Six types of grafts were performed, termed here "expanded sensory areas", estimated to contain the presumptive territory of specific sensory patches (dark colour) together with small portions of nearby prospective non-sensory epithelium (light colour), in accordance with (Sánchez-Guardado et al. 2014). (**c**) Schematic transverse section through the otic placode at the level of rh4 showing the Type 1 graft (light and dark blue; between arrows in **c**). The grafted territories affected exclusively a small portion of the otic placode, preventing any contribution of the hindbrain and other embryonic epithelial structures close to the otic placode. The dotted lines in **b** and **c** indicate the three subdivisions considered in a previous fate mapping study (Sánchez-Guardado et al. 2014). ac, anterior crista; asc, anterior semicircular canal; bp, basila papilla; EP, epidermis; ea, endolymphatic apparatus; lc, lateral crista; lsc; lateral semicircular canal; ml, macula lagena; mn, macula neglecta; ms, macula sacculi; mu, macula utriculi; pc, posterior crista; psc, posterior; semicircular canal; rh, rhombomere; s, saccule; tv, tegmentum vasculosum; u, utricle.

Figure 2. Graft-derived quail ganglionic neurons in the vestibular ganglion (VG). QCPN-stained grafted quail neurons (arrows in **a-f**) were clearly present in horizontal sections through the VG of all our chimaeric embryos (Types 1-6 in Fig. 1**b**). The larger size of the ganglionic neurons differentiated from the grafted otic epithelium (arrows) easily allows them to be distinguished from mesenchymal cells included in the graft (arrowheads). Abbreviation: A, anterior; bp, basilar papilla; cd, cochlear duct; HB, hindbrain; M, medial; R, rostral.

Figure 3. Graft-derived quail ganglionic neurons in the acoustic ganglion (AG). QCPN-stained grafted quail neurons (arrows in **a-f**) were present in the AG in horizontal sections through all our Type 1-5 chimaeric embryos (**a-e**). In contrast, the AG of Type 6 experimental embryos was devoid of QCPN-stained neurons (**f**). The arrowheads point to QCPN-stained mesenchymal cells. Abbreviation: A, anterior; bp, basilar papilla; cd, cochlear duct; HB, hindbrain; M, medial; R, rostral.

Figure 4. Labeling obtained from the expanded macula utriculi area. (**a**) Schematic representation of the Type 1 experiment at the 10-somite stage, involving the macula utriculi area (n = 9). (**b-k**) Horizontal sections through a representative Type 1 chimaeric embryo at 10 days of incubation (E10). The antibodies used are indicated in each panel. The grafted quail sensory cells were detected exclusively in the macula utriculi area (between arrowheads in **b**). QN-positive dendritic fibres from related labeled ganglion cells were detected in all sensory patches (arrowheads; ac, **c**; lc, **d**, pc, **e**, **h**; mu, **f**; ms, **g**; mn, **h**; bp, **i**, **j**; ml, **k**). Regarding the maculae, the utricular and saccular maculae (**f, g**) received more QN-stained processes than the rest (mn, **h**; ml, **k**). The entire basilar papilla was innervated by grafted afferent neurons (bp; **i, j**). (**l**) Diagram summarizing all these results. To illustrate qualitatively the number of QN-stained processes, a thick arrow means an abundant number, an intermediate arrow means a moderate number, and a thin arrow means a small number. M, medial; R, rostral. cd, cochlear duct; *d*-bp, distal basilar papilla; *p*-bp, proximal basilar papilla; u, utricle; s, saccule.

Figure 5. Labeling obtained from the expanded macula sacculi area. (**a**) Schematic representation of the Type 2 experiment at the 10-somite stage involving the macula sacculi area (n = 9). (**b-k**) Horizontal sections through a Type 2 chimaeric embryo at E10. The grafted quail cells were detected exclusively in the macula sacculi area (between arrowheads in **b**). QN-positive fibres were clearly detected in all sensory patches (arrowheads; ac, **c**; lc, **d**, pc, **e, h**; mu, **f**; ms, **g**; mn, **h**; bp, **i-k**; ml, **l**). All cristae and maculae received a high number of QN-stained fibres (**c-h, l**). Regarding the basilar papilla (bp), the intermediate and distal portions were innervated by grafted afferent neurons (*i*-bp and *d*-bp; **j, k**), but not the proximal basilar papilla (*p*-bp; **i**). (**m**) Diagram summarizing all these results. Same code as in Fig. 2**l**. M, medial; R, rostral.

Figure 6. Labeling obtained from the expanded basilar papilla area. (**A**) Schematic representation of the Type 3 experiment at the 10-somite stage involving the entire basilar papilla area (n = 8). (**b-k**) Horizontal sections through a Type 3 chimaeric embryo at E10. Grafted quail cells were detected exclusively in the basilar papilla area (between arrowheads in **b**). Numerous QN-positive dendrites were clearly detected in all sensory patches (arrowheads; ac, **c**, **c'**; lc, **d**; cp, **e**, **h**; mu, **f**; ms, **g**; mn, **h**; *i*-bp, **i, i'**; d-bp, **j**; ml, **k**). The macula lagena seemed to receive fewer QN-stained dendrites (ml, **k**) than the

other maculae. The anterior crista and the intermediate basilar papilla showed a small number of QN-positive dendrites (ac, **c**, **c'**; *i*-bp, **i**, **i'**), whereas the proximal basilar papilla was completely devoid of them (not shown). (**l**) Diagram summarizing all these results. M, medial; R, rostral.

Figure 7. Labeling obtained from the expanded lagena/neglecta maculae area. (**A**) Schematic representation of the Type 4 experiment at the 10-somite stage including the macula lagena and macula neglecta areas (n = 8). (**b-l**) Horizontal sections through one Type 4 chimaeric embryo at E10. Grafted quail cells were detected in the macula lagena (between arrowheads in **b**) as well as in the macula neglecta (between arrowheads in **c**). QN-positive processes were observed in all sensory patches (arrowheads; ac, **d**, **d'**; lc, **e**; pc, **f**, **i**; mu, **g**, **h**; ms, **h**; mn, **i**; *i*-bp, **j**; *d*-bp, **k**; ml, **l**). The posterior crista (**f**), the macula neglecta (**i**), the distal basilar papilla (*d*-bp, **k**), and the macula lagena (**l**) presented a considerable number of QN-stained dendrites. The anterior and lateral cristae (**d**, **d'**, **e**) and the utricular and saccular maculae (**g**, **h**) displayed very few QN-positive dendrites. The proximal and intermediate portions of the basilar papilla were completely devoid of QN-stained dendrites (see **j** for *i*-bp). (**m**) Diagram summarizing all these results. M, medial; R, rostral.

Figure 8. Labeling obtained from the expanded anterior/lateral cristae area. (**a**) Schematic representation of the Type 5 experiment at the 10-somite stage, including the presumptive areas of the anterior and posterior ampullary cristae (n = 7). (**b-l**) Horizontal sections through one Type 5 chimaeric embryo at E10. Grafted QCPN-positive cells were detected in the anterior and lateral cristae (between arrowheads in **b** and **c**). A large number of QN-positive dendrites were observed at the anterior crista (arrowheads in ac, **d**). QN-stained dendrites were detected also at the lateral crista (lc, **e**), the macula sacculi (ms, **h**), and the distal basilar papilla (*d*-bp, **k**). In contrast, the macula utriculi (mu, **g**), the intermediate basilar papilla (*i*-bp; **j**), the posterior crista (pc, **f** and **i**), the macula lagena (ml, **l**), and the macula neglecta (mn, **i**) presented few QN-stained processes. The proximal basilar papilla (not shown) was completely devoid of labeled quail dendrites. (**m**) Diagram summarizing all these results. M, medial; R, rostral.

Figure 9. Labeling obtained from the expanded posterior crista area. (**a**) Schematic representation of the Type 6 experiment at the 10-somite stage, involving the posterior

crista area (n = 6). (**b**-**f**) Horizontal sections through one Type 6 chimaeric embryo at E10. The posterior crista was the only sensory area included in the graft (between arrowheads in **b**). QN-positive fibres (arrowheads) were detected in the anterior and posterior cristae (ac, **c**; pc, **d**). A few QN-positive dendrites were observed in the lateral crista (pc, **e**, **e'**) and in the macula sacculi (ms, **f**, **f'**). (**g**) Diagram summarizing all these results. M, medial; R, rostral.

S1 Figure. Related to Figure 4. Grafted area of Type 1 graft. (**a**) Schematic representation of the Type 1 experiment at the 10-somite stage, involving the macula utriculi area. (**b**-**g**) Horizontal sections through a representative Type 1 chimaeric embryo at 10 days of incubation (E10). The QCPN-positive grafted area contained exclusively the macula utriculi (between arrowheads in **b**, **d**) and a contiguous small area in the utricle wall (arrows in **b**, **d**). The rest of the sensory and non-sensory elements were completely devoid of QCPN-positive grafted quail cells (ac, pc, and mn in **c**, **c'**; lc and mu in **d**, **d'**; bp in **e**-**g**; ml in **g**). Differentiated neurons from the grafted area were also observed (arrows in **e**, **f**). (**h**, **i**) Three-dimensional diagrams of a chimaeric inner ear summarizing the Type 1 grafted-cell distribution. The horizontal sections are indicated in **h** and **i**. Abbreviations: C, caudal; D, dorsal; M, medial; R, rostral.

S2 Figure. Related to Figure 5. Grafted area of Type 2 graft. (**a**) Schematic representation of the Type 2 experiment at the 10-somite stage, involving the macula sacculi area. (**b**-**e**) Horizontal sections through a representative Type 2 chimaeric embryo at 10 days of incubation (E10). The QCPN-positive grafted area contained exclusively the macula sacculi (between arrowheads in **b**, **d**) and a contiguous small area in the saccule wall (arrows in **b**, **d**). The rest of the sensory and non-sensory elements were completely devoid of QCPN-positive grafted quail cells (ac, pc, and mn in **c**, **c'**; lc and mu in **d**; bp in **e**; ml, not shown). (**f**, **g**) Three-dimensional diagrams of a chimaeric inner ear summarizing the Type 2 grafted-cell distribution. The horizontal sections are indicated in **f** and **g**. Abbreviations: C, caudal; D, dorsal; M, medial; R, rostral.

S3 Figure. Related to Figure 6. Grafted area of Type 3 graft. (**a**) Schematic representation of the Type 3 experiment at the 10-somite stage, involving the entire basilar papilla area. (**b**-**e**) Horizontal sections through a representative Type 3 chimaeric embryo at 10 days of incubation (E10). The QCPN-positive grafted area contained exclusively

the basilar papilla (between arrowheads in **b**, **e**) and a contiguous small area in the cochlear duct wall (arrows in **b**, **e**). The rest of the sensory and non-sensory elements were completely devoid of QCPN-positive grafted quail cells (ac, pc, and mn in **c**, **c'**; lc, mu, and ms in **d**; ml in **f**). (**f**, **g**) Three-dimensional diagrams of a chimaeric inner ear summarizing the Type 3 grafted-cell distribution. The horizontal sections are indicated in **f** and **g**. Abbreviations: C, caudal; D, dorsal; M, medial; R, rostral.

S4 Figure. Related to Figure 7. Grafted area of Type 4 graft. (**a**) Schematic representation of the Type 4 experiment at the 10-somite stage, involving the macula lagena and macula neglecta areas. (**b-f**) Horizontal sections through a representative Type 4 chimaeric embryo at 10 days of incubation (E10). The QCPN-positive grafted area contained exclusively the macula lagena and macula neglecta areas (between arrowheads in **b**, **c**) and their contiguous non-sensory areas (arrows in **b**, **c**, **d**). The rest of the sensory and non-sensory elements were completely devoid of QCPN-positive grafted quail cells (ac and pc in **d**; lc, mu, and ms in **e**; bp in **f**). Differentiated neurons from the grafted area were also observed (arrow in **f**). The graft formed a dorsoventrally arranged band in the cochlear duct (arrowheads in **e**, **f**). (**g**, **h**) Three-dimensional diagrams of a chimaeric inner ear summarizing the Type 4 grafted-cell distribution. The horizontal sections are indicated in **g** and **h**. Abbreviations: C, caudal; D, dorsal; M, medial; R, rostral.

S5 Figure. Related to Figure 8. Grafted area of Type 5 graft. (**a**) Schematic representation of the Type 5 experiment at the 10-somite stage, involving the anterior and lateral cristae area. (**b-e**) Horizontal sections through a representative Type 5 chimaeric embryo at 10 days of incubation (E10). The QCPN-positive grafted area contained exclusively the anterior and lateral cristae area (between arrowheads in **b**, **c**, **d**) and their contiguous non-sensory areas (arrows in **b**, **c**, **d**). The rest of the sensory and non-sensory elements were completely devoid of QCPN-positive grafted quail cells (pc in **d'**; lc, mu, and ms in **d**; bp in **e**, **f**; ml in **f**). Some QCPN-stained cells from the grafted mesenchyme were also observed (short arrows in **f**). Differentiated neurons from the grafted area were also observed (large arrows in **f**, **e**). (**g**, **h**) Three-dimensional diagrams of a chimaeric inner ear summarizing the Type 5 grafted-cell distribution. The horizontal sections are indicated in **g** and **h**. Abbreviations: C, caudal; D, dorsal; M, medial; R, rostral.

S6 Figure. Related to Figure 9. Grafted area of Type 6 graft. (**a**) Schematic representation of the Type 6 experiment at the 10-somite stage, involving the posterior crista area. (**b-e**) Horizontal sections through a representative Type 6 chimaeric embryo at 10 days of incubation (E10). The QCPN-positive grafted area contained exclusively the posterior crista area (between arrowheads in **b**, **c**) and its contiguous non-sensory areas (arrows in **b**, **c**). The rest of the sensory and non-sensory elements were completely devoid of QCPN-positive grafted quail cells (ac and mn in **c**; lc, mu, and ms in **d**; bp and ml in **e**). (**f**, **g**) Three-dimensional diagrams of a chimaeric inner ear summarizing the Type 6 grafted-cell distribution. The horizontal sections are indicated in **f** and **g**. Abbreviations: C, caudal; D, dorsal; M, medial; R, rostral.

Table 1. Overall summary of all types of experiments, indicating the homotopically grafted placodal areas and the sensory patches to which the correlative grafted neuroblasts projected. The percentage of the area of each mature sensory patch innervated by grafted neurons with respect to its whole area was calculated in each experimental type. The number of asterisks indicates the relative quantity of QN-positive processes reaching each sensory element: ***, many (an innervated area of 67-100%); **, a moderate number (an innervated area of 34-66%); *, few (an innervated area of 1-33%); +, occasional processes observed in some embryos. This asterisk code corresponds to the arrow thicknesses used in the summarizing diagrams of Figs. 1-6 (***, thick arrow; **, intermediate thickness arrow; *, thin arrow, +, thin broken line). The arithmetic mean and the standard deviation, as well as the number of grafts of each type, were indicated.

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Table 1

			INNERVATED SENSORY PATCH									
			mu	**ms**	**ac**	**lc**	***p*-bp**	***i*-bp**	***d*-bp**	**ml**	**mn**	**pc**
GRAFTED AREA	**mu**	**Type 1** n = 9	*** 83±7	*** 89±6	** 44±4	** 40±3	*** 79±4	*** 85±5	** 43±7	** 46±4	** 39±7	** 53±7
	ms	**Type 2** n = 9	*** 92±3	*** 83±6	*** 71±6	*** 72±5	0±0	* 4±2	** 36±7	*** 73±7	*** 77±8	*** 87±5
	bp	**Type 3** n = 8	*** 81±4	*** 73±4	* 10±3	** 40±5	0±0	* 9±9	** 48±7	** 49±5	*** 70±3	*** 74±4
	ml/mn	**Type 4** n = 8	* 27±6	* 24±4	* 14±5	* 26±7	0±0	0±0	** 40±7	** 45±3	** 35±9	*** 76±7
	ac/lc	**Type 5** n = 7	* 8±2	*** 71±6	*** 76±5	* 23±3	0±0	**	**	*	* 18±3	* 30±5
	pc	**Type 6** n = 6	0±0	+ 1±0	* 7±1	+ 1±0	0±0	0±0	0±0	0±0	0±0	* 5±1