

active space of dipole source detection The overlapping roles of the inner ear and lateral line: the

Christopher B. Braun and Sheryl Coombs

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The overlapping roles of the inner ear The overlapping roles of the inner ear
and lateral line: the active space of dipole pping roles of the in
ne: the active space
source detection

Christopher B. Braun* **and Sheryl Coombs**

Parmly Hearing Institute, Loyola University Chicago, 6525 North Sheridan Road, Chicago, IL 60626, USA

Parmly Hearing Institute, Loyola University Chicago, 6525 North Sheridan Road, Chicago, IL 60626, USA
The problems associated with the detection of sounds and other mechanical disturbances in the aquatic
environment differ The problems associated with the detection of sounds and other mechanical disturbances in the aquatic
environment differ greatly from those associated with airborne sounds. The differences are primarily due
to the incompre The problems associated with the detection of sounds and other mechanical disturbances in the aquatic
environment differ greatly from those associated with airborne sounds. The differences are primarily due
to the incompre environment differ greatly from those associated with airborne sounds. The differences are primarily due
to the incompressibility of water and the corresponding increase in importance of the acoustic near field.
The near f to the incompressibility of water and the corresponding increase in importance of the acoustic near field.
The near field, or hydrodynamic field, is characterized by steep spatial gradients in pressure, and detection of th The near field, or hydrodynamic field, is characterized by steep spatial gradients in pressure, and detection of the accelerations associated with these gradients is performed by both the inner ear and the lateral line sys tion of the accelerations associated with these gradients is performed by both the inner ear and the lateral line systems of fishes. Acceleration-sensitive otolithic organs are present in all fishes and provide these anima lateral line systems of fishes. Acceleration-sensitive otolithic organs are present in all fishes and provide
these animals with a form of inertial audition. The detection of pressure gradients, by both the lateral
line an these animals with a form of inertial audition. The detection of pressure gradients, by both the lateral
line and inner ear, is the taxonomically most widespread mechanism of sound-source detection amongst
vertebrates, and line and inner ear, is the taxonomically most widespread mechanism of sound-source detection amongst
vertebrates, and is thus the most likely primitive mode of detecting sound sources. Surprisingly, little is
known about t vertebrates, and is thus the most likely primitive mode of detecting sound sources. Surprisingly, little is known about the capabilities of either the lateral line or the otolithic endorgan in the detection of vibratory di known about the capabilities of either the lateral line or the otolithic endorgan in the detection of vibra-
tory dipole sources. Theoretical considerations for the overlapping roles of the inner ear and lateral line
syste tory dipole sources. Theoretical considerations for the overlapping roles of the inner ear and lateral line
systems in midwater predict that the lateral line will operate over a shorter distance range than the inner
ear, a systems in midwater predict that the lateral line will operate over a shorter distance range than the inner ear, although with a much greater spatial resolution. Our empirical results of dipole detection by mottled sculpin ear, although with a much greater spatial resolution. Our empirical results of dipole detection by mottled sculpin, a benthic fish, do not agree with theoretical predictions based on midwater fishes, in that the distance r sculpin, a benthic fish, do not agree with theoretical predictions based on midwater fishes, in that the distance ranges of the two systems appear to be approximately equal. This is almost certainly as a result of physical distance ranges of the two systems appear to be approximately equal. This is almost certainly as a result of physical coupling between the fishes and the substrate. Thus, rather than having a greater active range, the inne of physical coupling between the fishes a
the inner ear appears to have a reduce
range may be concomitantly extended. the inner ear appears to have a reduced distance range in benthic fishes, and the lateral line distance range may be concomitantly extended.
 Keywords: hearing; mechanosensory; auditory; multisensory

1. SOUND DETECTION UNDERWATER: THE PRIMACY CTION UNDERWATER: TH
OF THE NEAR FIELD **OF THE NEAR FIELD**
The mechanisms of sound perception by aquatic organ-

The mechanisms of sound perception by aquatic organisms are often difficult to appreciate fully since the nature
of sound and sound sources can be so different in air and The mechanisms of sound perception by aquatic organisms are often difficult to appreciate fully since the nature
of sound and sound sources can be so different in air and
in water. We commonly define sound as a propagating isms are often difficult to appreciate fully since the nature
of sound and sound sources can be so different in air and
in water. We commonly define sound as a propagating
wave of compressions and rarefactions of the condu of sound and sound sources can be so different in air and
in water. We commonly define sound as a propagating
wave of compressions and rarefactions of the conducting in water. We commonly define sound as a propagating
wave of compressions and rarefactions of the conducting
medium, but this pressure wave is only one portion of the
stimulus field surrounding a vibratory source. If the wave of compressions and rarefactions of the conducting
medium, but this pressure wave is only one portion of the
stimulus field surrounding a vibratory source. If the
medium is relatively incompressible as water is then medium, but this pressure wave is only one portion of the
stimulus field surrounding a vibratory source. If the
medium is relatively incompressible, as water is, then
other aspects of the stimulus field ascend in importanc stimulus field surrounding a vibratory source. If the medium is relatively incompressible, as water is, then other aspects of the stimulus field ascend in importance. medium is relatively incompressible, as water is, then
other aspects of the stimulus field ascend in importance.
Any mechanical disturbance, such as the vibrations of an
annendage the burrowing or swimming motions of appendage, the burrowing or swimming motions of Any mechanical disturbance, such as the vibrations of an appendage, the burrowing or swimming motions of animals and communicatory stridulations or vocalizations will generate a steep gradient in pressure close to appendage, the burrowing or swimming motions of
animals and communicatory stridulations or vocaliza-
tions, will generate a steep gradient in pressure close to
the source whether or not they actually give rise to the animals and communicatory stridulations or vocaliza-
tions, will generate a steep gradient in pressure close to
the source, whether or not they actually give rise to the
propagating pressure wave we commonly label 'sound' tions, will generate a steep gradient in pressure close to
the source, whether or not they actually give rise to the
propagating pressure wave we commonly label 'sound'.
Given the incompressibility of water, this steep gra the source, whether or not they actually give rise to the propagating pressure wave we commonly label 'sound'.
Given the incompressibility of water, this steep gradient propagating pressure wave we commonly label 'sound'.
Given the incompressibility of water, this steep gradient
in pressure will give rise to a net flow of water. Close to
the source this bulk water flow will eclipse the ma Given the incompressibility of water, this steep gradient
in pressure will give rise to a net flow of water. Close to
the source, this bulk water flow will eclipse the magnitude
of the oscillatory compressions and rarefact in pressure will give rise to a net flow of water. Close to
the source, this bulk water flow will eclipse the magnitude
of the oscillatory compressions and rarefactions (particle
motions) that make un the propagating press the source, this bulk water flow will eclipse the magnitude of the oscillatory compressions and rarefactions (particle motions) that make up the propagating pressure wave. Thus for many, particularly low frequency, sources, this

acoustic near field is of utmost biological importance. acoustic near field is of utmost biological importance.
Detection of the particle accelerations associated with
these pressure gradients is almost certainly the primitive acoustic near field is of utmost biological importance.
Detection of the particle accelerations associated with
these pressure gradients is almost certainly the primitive
mode of vertebrate hearing (Kalmiin 1989) and remai Detection of the particle accelerations associated with
these pressure gradients is almost certainly the primitive
mode of vertebrate hearing (Kalmijn 1989) and remains
the most taxonomically widespread. These steep gradie these pressure gradients is almost certainly the primitive
mode of vertebrate hearing (Kalmijn 1989) and remains
the most taxonomically widespread. These steep gradients
in pressure surrounding a hydrodynamic source are al mode of vertebrate hearing (Kalmijn 1989) and remains
the most taxonomically widespread. These steep gradients
in pressure surrounding a hydrodynamic source are also
detected by the lateral line system. Both the lateral li the most taxonomically widespread. These steep gradients
in pressure surrounding a hydrodynamic source are also
detected by the lateral line system. Both the lateral line
and the inner ear, then are responsive to many of t in pressure surrounding a hydrodynamic source are also detected by the lateral line system. Both the lateral line and the inner ear, then, are responsive to many of the same stimulus fields. In order to understand the function of either system, or the primitive mode of sound detection generally, it is imperative to move beyond specula same stimulus fields. In order to understand the function
of either system, or the primitive mode of sound detection
generally, it is imperative to move beyond speculative
evolutionary considerations of the relationship be of either system, or the primitive mode of sound detection generally, it is imperative to move beyond speculative
evolutionary considerations of the relationship between
auditory and lateral line systems and actually begin to
investigate the overlap in the functions of these two evolutionary considerations of the relationship between
auditory and lateral line systems and actually begin to
investigate the overlap in the functions of these two
systems that detect different aspects of the same source auditory and lateral line systems and actually begin to investigate the overlap in the functions of these two
systems that detect different aspects of the same sources.
We have been investigating the relative contributions restigate the overlap in the functions of these two
stems that detect different aspects of the same sources.
We have been investigating the relative contributions of
the sensory systems to the detection and analysis of

systems that detect different aspects of the same sources.
We have been investigating the relative contributions of
both sensory systems to the detection and analysis of
vibratory dinole sources by the Lake Michigan mottle We have been investigating the relative contributions of
both sensory systems to the detection and analysis of
vibratory dipole sources by the Lake Michigan mottled
sculpin (Cottus hairdi) a benthic fish that uses sound a both sensory systems to the detection and analysis of vibratory dipole sources by the Lake Michigan mottled sculpin *(Cottus bairdi*), a benthic fish that uses sound and vibratory dipole sources by the Lake Michigan mottled
sculpin *(Cottus bairdi)*, a benthic fish that uses sound and
vibration to detect prey, particularly in the absence of
visual cuse (Hoekstra & Janssen 1985) Cottids in sculpin (*Cottus bairdi*), a benthic fish that uses sound and
vibration to detect prey, particularly in the absence of
visual cues (Hoekstra & Janssen 1985). Cottids in general
lack a swimbladder and are apparently insensi vibration to detect prey, particularly in the absence of
visual cues (Hoekstra & Janssen 1985). Cottids in general
lack a swimbladder and are apparently insensitive to pres-
sure her se but have a typical complement of oto visual cues (Hoekstra & Janssen 1985). Cottids in general lack a swimbladder and are apparently insensitive to pressure *per se* but have a typical complement of otolithic lack a swimbladder and are apparently insensitive to pressure $per\ se$ but have a typical complement of otolithic endorgans, and could use inertial audition to detect sound sources. Mottled sculpin have a lateral line that i sure *per se* but have a typical complement of otolithic endorgans, and could use inertial audition to detect sound sources. Mottled sculpin have a lateral line that is typical of Scorpaeniformes with simple canals on the endorgans, and could use inertial audition to detect sound
sources. Mottled sculpin have a lateral line that is typical
of Scorpaeniformes, with simple canals on the surface of

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scale between the lateral line system and the inner ear. The
lateral line (at the top of the field), with multiple closely Figure 1. (*a*) Illustration of the difference in sampling
scale between the lateral line system and the inner ear. The
lateral line (at the top of the field), with multiple closely
spaced sampling points, requires a stee scale between the lateral line system and the inner ear. The lateral line (at the top of the field), with multiple closely
spaced sampling points, requires a steep spatial gradient to
achieve stimulation, but is canable of lateral line (at the top of the field), with multiple closely
spaced sampling points, requires a steep spatial gradient to
achieve stimulation, but is capable of resolving that gradient
in fine spatial detail. The auditory spaced sampling points, requires a steep spatial gradient to
achieve stimulation, but is capable of resolving that gradient
in fine spatial detail. The auditory system of a sculpin may
respond to a similar pressure gradien achieve stimulation, but is capable of resolving that gradient
in fine spatial detail. The auditory system of a sculpin may
respond to a similar pressure gradient, but by integrating
the differences in pressure along oppos in fine spatial detail. The auditory system of a sculpin may
respond to a similar pressure gradient, but by integrating
the differences in pressure along opposing sides of the entire
body (note the difference in scale of a respond to a similar pressure gradient, but by integrating
the differences in pressure along opposing sides of the entir
body (note the difference in scale of a fish body, bottom,
and any single canal segment, above). The the differences in pressure along opposing sides of the entire
body (note the difference in scale of a fish body, bottom,
and any single canal segment, above). The inertial sensors
of the inner ear are thus incapable of re body (note the difference in scale of a fish body, bottom,
and any single canal segment, above). The inertial sensor:
of the inner ear are thus incapable of resolving the fine
spatial detail of the stimulus field. Isonress and any single canal segment, above). The inertial sensors
of the inner ear are thus incapable of resolving the fine
spatial detail of the stimulus field. Isopressure contours
were modelled after dipole flow field equation % of the inner ear are thus incapable of resolving the fine
spatial detail of the stimulus field. Isopressure contours
were modelled after dipole flow field equations (Kalmijn
1988) (b) Modelled accelerations of the canal spatial detail of the stimulus field. Isopressure contours
were modelled after dipole flow field equations (Kalmijn
1988). (*b*) Modelled accelerations of the canal fluid in
response to a vibrating dipole. The peak acceler were modelled after dipole flow field equations (Kalmijn
1988). (b) Modelled accelerations of the canal fluid in
response to a vibrating dipole. The peak acceleration along
a linear canal positioned at a range of distances 1988). (*b*) Modelled accelerations of the canal fluid in
response to a vibrating dipole. The peak acceleration along
a linear canal positioned at a range of distances from an
orthogonally vibrating source (as in the beha response to a vibrating dipole. The peak acceleration a
a linear canal positioned at a range of distances from a
orthogonally vibrating source (as in the behavioural
experiments discussed in the text) is plotted as a funct a linear canal positioned at a range of distances from an
orthogonally vibrating source (as in the behavioural
experiments discussed in the text) is plotted as a function
of source distance. The onen squares represent the orthogonally vibrating source (as in the behavioural
experiments discussed in the text) is plotted as a function
of source distance. The open squares represent the net accelerations of canal fluids in a midwater, neutrally of source distance. The open squares represent the net
accelerations of canal fluids in a midwater, neutrally
buoyant fish. The open circles represent the accelerations
of canal fluids in a benthic fish that does not move accelerations of canal fluids in a midwater, neutrally
buoyant fish. The open circles represent the accelerations
of canal fluids in a benthic fish that does not move at all
as a result of the imposed sound field. Note the buoyant fish. The open circles represent the accelerations
of canal fluids in a benthic fish that does not move at all
as a result of the imposed sound field. Note the difference
in the slopes of the two functions of canal fluids in a benthic fish that does not move at all
as a result of the imposed sound field. Note the difference
in the slopes of the two functions.

the head and a single trunk canal. A small number of
superficial neuromasts are also present paralleling the the head and a single trunk canal. A small number of
superficial neuromasts are also present paralleling the
main canals and in independent lines on the head and the head and a single trunk canal. A small number of
superficial neuromasts are also present paralleling the
main canals and in independent lines on the head and
tail (Janssen *et al.* 1987) Several lines of evidence indic superficial neuromasts are also present paralleling the main canals and in independent lines on the head and tail (Janssen *et al.* 1987). Several lines of evidence indicate main canals and in independent lines on the head and
tail (Janssen *et al.* 1987). Several lines of evidence indicate
that the superficial neuromasts play a negligible role in
dinole source detection (Coombs & Braun 2000) tail (Janssen *et al.* 1987). Several lines of evidence indicate that the superficial neuromasts play a negligible role in dipole source detection (Coombs & Braun 2000), so we will restrict the present discussion to canal that the superficial neuromasts play a negligible role in
dipole source detection (Coombs & Braun 2000), so we
will restrict the present discussion to canal neuromasts.
Our experiments have focused on the distance range of dipole source detection (Coombs & Braun 2000), so we
will restrict the present discussion to canal neuromasts.
Our experiments have focused on the distance range of will restrict the present discussion to canal neuromasts.
Our experiments have focused on the distance range of
the lateral line and the inner ear in an attempt to define
an active space within which each system operates. Our experiments have focused on the distance range of
the lateral line and the inner ear in an attempt to define
an active space within which each system operates. Only
then can we begin to address questions of spatial or an active space within which each system operates. Only then can we begin to address questions of spatial or an active space within which each system operates. Only
then can we begin to address questions of spatial or
temporal resolution of hydrodynamic source localization
and perception then can we begit
temporal resolution
and perception.
Before turning mporal resolution of hydrodynamic source localization
d perception.
Before turning to our behavioural data, it is necessary
explore the roles each sensory system might theoreti-

and perception.
Before turning to our behavioural data, it is necessary
to explore the roles each sensory system might theoreti-Before turning to our behavioural data, it is necessary
to explore the roles each sensory system might theoreti-
cally play in the detection of the pressure gradients.
Although both the lateral line and otolithic organs ar to explore the roles each sensory system might theoretically play in the detection of the pressure gradients.
Although both the lateral line and otolithic organs are
responsive to the same stimulus fields the mechanisms of cally play in the detection of the pressure gradients.
Although both the lateral line and otolithic organs are
responsive to the same stimulus fields, the mechanisms of
transduction and thus the type of information extract Although both the lateral line and otolithic organs are responsive to the same stimulus fields, the mechanisms of transduction and thus the type of information extracted responsive to the same stimulus fields, the mechanisms of
transduction and thus the type of information extracted
differ greatly. Accelerations of the water surrounding a
vibratory source are efficiently transmitted to a n transduction and thus the type of information extracted
differ greatly. Accelerations of the water surrounding a
vibratory source are efficiently transmitted to a nearby
fish due to the similarity in density of the fish an differ greatly. Accelerations of the water surrounding a vibratory source are efficiently transmitted to a nearby fish due to the similarity in density of the fish and the surrounding water. The otoliths having a greater d vibratory source are efficiently transmitted to a nearby
fish due to the similarity in density of the fish and the
surrounding water. The otoliths, having a greater density,
will lag behind the motions of the fish providin fish due to the similarity in density of the fish and the
surrounding water. The otoliths, having a greater density,
will lag behind the motions of the fish, providing the
animal with three-dimensional cues to the motions surrounding water. The otoliths, having a greater density,
will lag behind the motions of the fish, providing the
animal with three-dimensional cues to the motions of its
own body (Fay 1984) This inertial form of audition will lag behind the motions of the fish, providing the animal with three-dimensional cues to the motions of its own body (Fay 1984). This inertial form of audition will animal with three-dimensional cues to the motions of its
own body (Fay 1984). This inertial form of audition will
be particularly important within the acoustic near field,
where bulk flow predominates, but it may also be o own body (Fay 1984). This inertial form of audition will
be particularly important within the acoustic near field,
where bulk flow predominates, but it may also be of
importance within the intermediate or far field allowin be particularly important within the acoustic near field,
where bulk flow predominates, but it may also be of
importance within the intermediate or far field, allowing
the animal to detect the particle displacements that m where bulk flow predominates, but it may also be of importance within the intermediate or far field, allowing the animal to detect the particle displacements that make importance within the intermediate or far field, allowing
the animal to detect the particle displacements that make
up the propagating pressure wave (Kalmijn 1988). Close
to the source, the steep gradients of pressure will the animal to detect the particle displacements that make
up the propagating pressure wave (Kalmijn 1988). Close
to the source, the steep gradients of pressure will give rise
to highly non-uniform patterns of water flow. T up the propagating pressure wave (Kalmijn 1988). Close
to the source, the steep gradients of pressure will give rise
to highly non-uniform patterns of water flow. The
spatially distributed accelerometers of the lateral lin to the source, the steep gradients of pressure will give rise
to highly non-uniform patterns of water flow. The
spatially distributed accelerometers of the lateral line
system are well suited to resolving the fine spatial spatially distributed accelerometers of the lateral line spatially distributed accelerometers of the lateral line
system are well suited to resolving the fine spatial
organization of these pressure gradients. In principle, the
accelerations imparted to the lateral line canal flu system are well suited to resolving the fine spatial
organization of these pressure gradients. In principle, the
accelerations imparted to the lateral line canal fluid are
similar to those imparted to the fish itself. In t organization of these pressure gradients. In principle, the accelerations imparted to the lateral line canal fluid are similar to those imparted to the fish itself. In the case of the fish pressure differences between oppo accelerations imparted to the lateral line canal fluid are
similar to those imparted to the fish itself. In the case of
the fish, pressure differences between opposing sides of the
hody give rise to accelerations of the wh similar to those imparted to the fish itself. In the case of
the fish, pressure differences between opposing sides of the
body give rise to accelerations of the whole body. In the
case, of the lateral line, system, pressur the fish, pressure differences between opposing sides of the body give rise to accelerations of the whole body. In the case of the lateral line system, pressure differences body give rise to accelerations of the whole body. In the case of the lateral line system, pressure differences between adjacent canal pores give rise to accelerations of the fluid within that canal segment. This differenc case of the lateral line system, pressure differences
between adjacent canal pores give rise to accelerations of
the fluid within that canal segment. This difference in the
size of the sampling interval (whole fish versus between adjacent canal pores give rise to accelerations of
the fluid within that canal segment. This difference in the
size of the sampling interval (whole fish versus single
canal segment) and sample numbers (single body the fluid within that canal segment. This difference in the size of the sampling interval (whole fish versus single canal segment) and sample numbers (single body versus size of the sampling interval (whole fish versus single
canal segment) and sample numbers (single body versus
multiple canal segments) predicts that within threshold
distances of the lateral line system, the lateral line w canal segment) and sample numbers (single body versus
multiple canal segments) predicts that within threshold
distances of the lateral line system, the lateral line will
always provide a greater spatial resolution of the s multiple canal segments) predicts that within threshold
distances of the lateral line system, the lateral line will
always provide a greater spatial resolution of the stimulus
field than the inner ear. This enhanced spatia distances of the lateral line system, the lateral line will always provide a greater spatial resolution of the stimulus field than the inner ear. This enhanced spatial resolution always provide a greater spatial resolution of the stimulus
field than the inner ear. This enhanced spatial resolution
may allow both a more detailed analysis of both the
spatial configuration of the field and the precise field than the inner ear. This enhanced spatial resolution
may allow both a more detailed analysis of both the
spatial configuration of the field and the precise location
of the source by the lateral line system (figure may allow both a more detailed analysis of both the spatial configuration of the field and the precise location of the source by the lateral line system (figure 1*a*). To date there have been no studies that directly exami spatial configuration of the field and the precise location
of the source by the lateral line system (figure $1a$). To date
there have been no studies that directly examine the
spatial resolution of either the lateral lin of the source by the lateral line system (figure l*a*). To date
there have been no studies that directly examine the
spatial resolution of either the lateral line or inertial
auditory systems there have been no studies that directly examine the spatial resolution of either the lateral line or inertial auditory systems.

In addition to this difference in sampling resolution, we auditory systems.
In addition to this difference in sampling resolution, we
must consider the difference in the mode of transduction
of the stimulus field by the lateral line system and the In addition to this difference in sampling resolution, we
must consider the difference in the mode of transduction
of the stimulus field by the lateral line system and the
inner ear. The inertial sensors of the inner ear d must consider the difference in the mode of transduction
of the stimulus field by the lateral line system and the
inner ear. The inertial sensors of the inner ear detect a
near field stimulus by measuring the motion impose of the stimulus field by the lateral line system and the inner ear. The inertial sensors of the inner ear detect a near field stimulus by measuring the motion imposed on inner ear. The inertial sensors of the inner ear detect a
near field stimulus by measuring the motion imposed on
the fish itself. The lateral line, on the other hand,
measures the motion imposed on the canal fluids. If the mear field stimulus by measuring the motion imposed on
the fish itself. The lateral line, on the other hand,
measures the motion imposed on the canal fluids. If these
canals are themselves moving the resulting motion the fish itself. The lateral line, on the other hand,
measures the motion imposed on the canal fluids. If these
canals are themselves moving, the resulting motion

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pressure difference at the two pores and the motion of the
canal itself, i.e. motion within the canals is proportional within the canal is the result of the difference between the
pressure difference at the two pores and the motion of the
canal itself, i.e. motion within the canals is proportional
to the difference in the motion of water o canal itself, i.e. motion within the canals is proportional
to the difference in the motion of water outside that canal canal itself, i.e. motion within the canals is proportional
to the difference in the motion of water outside that canal
and the motion of the canal itself (Denton & Gray 1983).
The motion of the fish therefore effectively to the difference in the motion of water outside that canal
and the motion of the canal itself (Denton & Gray 1983).
The motion of the fish therefore effectively reduces the
magnitude of fluid motion within the canal. The The motion of the fish therefore effectively reduces the magnitude of fluid motion within the canal. The degree The motion of the fish therefore effectively reduces the
magnitude of fluid motion within the canal. The degree
of reduction will depend on the relationship between the
orientation of the fish's motion and the orientation magnitude of fluid motion within the canal. The degree
of reduction will depend on the relationship between the
orientation of the fish's motion and the orientation of the
canals Additionally the decrease in lateral line s of reduction will depend on the relationship between the orientation of the decrease in lateral line stimula-
canals. Additionally, the decrease in lateral line stimula-
tion will increase with increasing source distance orientation of the fish's motion and the orientation of the canals. Additionally, the decrease in lateral line stimulation will increase with increasing source distance (figure $1b$). While the water motions outside the fish will tion will increase with increasing source distance (figure $1b$). While the water motions outside the fish will attenuate as the reciprocal of the distance cubed, the net water motions in the canals of a fish displaced by (figure $1b$). While the water motions outside the fish will attenuate as the reciprocal of the distance cubed, the net water motions in the canals of a fish displaced by a sound field will in the most extreme case modell attenuate as the reciprocal of the distance cubed, the net
water motions in the canals of a fish displaced by a sound
field will, in the most extreme case modelled by Denton
& Gray (1983) actually attenuate as the reciproc water motions in the canals of a fish displaced by a sound
field will, in the most extreme case modelled by Denton
& Gray (1983), actually attenuate as the reciprocal of the field will, in the most extreme case modelled by Denton & Gray (1983), actually attenuate as the reciprocal of the distance to the fourth power. Furthermore, Denton & Gray (1983) argue that when the distance to the source & Gray (1983), actually attenuate as the reciprocal of the distance to the fourth power. Furthermore, Denton & Gray (1983) argue that when the distance to the source is great relative to the length of the fish, the motions distance to the fourth power. Furthermore, Denton &
Gray (1983) argue that when the distance to the source is
great relative to the length of the fish, the motions of the
water will be very similar in magnitude along the e Gray (1983) argue that when the distance to the source is
great relative to the length of the fish, the motions of the
water will be very similar in magnitude along the entire
length of the fish-effectively eliminating any great relative to the length of the fish, the motions of the
water will be very similar in magnitude along the entire
length of the fish, effectively eliminating any lateral line
stimulation. They and many other subsequent water will be very similar in magnitude along the entire length of the fish, effectively eliminating any lateral line stimulation. They and many other subsequent workers length of the fish, effectively eliminating any lateral line
stimulation. They and many other subsequent workers
have therefore suggested that the distance range of both
the lateral line and the inner ear are related to th stimulation. They and many other subsequent workers
have therefore suggested that the distance range of both
the lateral line and the inner ear are related to the body
length of the fish but with differing relationships have therefore suggested that the distance range of both
the lateral line and the inner ear are related to the body
length of the fish, but with differing relationships.
Accordingly the inertial sensors of the inner ear ma the lateral line and the inner ear are related to the body
length of the fish, but with differing relationships.
Accordingly, the inertial sensors of the inner ear may be length of the fish, but with differing relationships.
Accordingly, the inertial sensors of the inner ear may be
responsive to distances in the order of several body
lengths but the lateral line would be limited to one or t Accordingly, the inertial sensors of the inner ear may be responsive to distances in the order of several body lengths but the lateral line would be limited to one or two times the body length at most even for relatively i responsive to distances in the order of several body
lengths but the lateral line would be limited to one or two
times the body length at most, even for relatively intense
sources sources.

2. EXPERIMENTAL PROCEDURES

2. EXPERIMENTAL PROCEDURES
We have used two behavioural approaches to explore the
ility of mettled equipin to detect a vibrating boad. Given the We have used two behavioural approaches to explore the ability of mottled sculpin to detect a vibrating bead. Given the theoretical considerations outlined above in δ l, and the many ability of mottled sculpin to detect a vibrating bead. Given the theoretical considerations outlined above in $\S 1$, and the many statements in the literature that the inner ear has a greater theoretical considerations outlined above in \S 1, and the many
statements in the literature that the inner ear has a greater
distance range than the lateral line, we chose to determine
empirically the distance range for statements in the literature that the inner ear has a greater
distance range than the lateral line, we chose to determine
empirically the distance range for both systems using a fixed
intensity dinals source presented to t empirically the distance range for both systems using a fixed intensity dipole source presented to the fishes at a range of distances. What is the maximum detectable distance of this intensity dipole source presented to the fishes at a range of intensity dipole source presented to the fishes at a range of
distances. What is the maximum detectable distance of this
source by the lateral line and inner ear? In all experiments, our
source was a vibrating head (6 mm d distances. What is the maximum detectable distance of this
source by the lateral line and inner ear? In all experiments, our
source was a vibrating bead (6 mm diameter), sinusoidally
driven by a minishalor with a diaplecem source was a vibrating bead (6mm diameter), sinusoidally
driven by a minishaker with a displacement of 3mm, accelersource was a vibrating bead (6mm diameter), sinusoidally
driven by a minishaker with a displacement of 3mm, acceler-
ating 300 m s^{-2} at 50 Hz . The axis of vibration was always
parallel to the long axis of the fis driven by a minishaker with a displacement of 3 mm, accelerating 300 m s^{-2} at 50 Hz . The axis of vibration was always parallel to the long axis of the fishes, and the bead was located along a transect originating parallel to the long axis of the fishes, and the bead was located along a transect originating at the centre of mass of the fishes
(at the level of the pelvic fin) and forming a right angle to the
long axis of the fishes. All experiments were performed either on (at the level of the pelvic fin) and forming a right angle to the (at the level of the pelvic fin) and forming a right angle to the
long axis of the fishes. All experiments were performed either on
enucleated animals or in darkness. All procedures conformed to
the Lavela University Insti long axis of the fishes. All experiments were performed either on
enucleated animals or in darkness. All procedures conformed to
the Loyola University Institutional Animal Care and Use
Committee suidelines the Loyola University Institutional Animal Care and Use Committee guidelines. Exploration University Institutional Animal Care and Use

mmittee guidelines.

Naive mottled sculpin will orientate to, approach, and even-

Committee guidelines.
Naive mottled sculpin will orientate to, approach, and even-
tually strike at a vibrating bead with high frequency. We used
the first component of this innate behaviour as a mosque of tually strike at a vibrating bead with high frequency. We used the first component of this innate behaviour as a measure of tually strike at a vibrating bead with high frequency. We used
the first component of this innate behaviour as a measure of
source detection in blinded animals. Briefly, animals were
placed in a large behavioural areas and the first component of this innate behaviour as a measure of
source detection in blinded animals. Briefly, animals were
placed in a large behavioural arena and videotaped from below.
We applyed the distribution of the chan source detection in blinded animals. Briefly, animals were
placed in a large behavioural arena and videotaped from below.
We analysed the distribution of the change in angle of the fishes
polative to the course (often the placed in a large behavioural arena and videotaped from below.
We analysed the distribution of the change in angle of the fishes
relative to the source (after the first response) during trials when
a signal was present and We analysed the distribution of the change in angle of the fishes
relative to the source (after the first response) during trials when
a signal was present and when a signal was absent over a range
of source distances (2, relative to the source (after the s
a signal was present and when
of source distances (2–20 cm).
We also used algorized appli of source distances $(2-20 \text{ cm})$.
We also used classical conditioning to determine the detect-

ability of the same source in a similar configuration. In this

Figure 2. (*a*) Dipole source detection by the mottled sculpin, Figure 2. (a) Dipole source detection by the mottled sculpin,
plotted as a function of source distance. The detectability of
the source $(h(A))$ which decreases with source distance fell Figure 2. (*a*) Dipole source detection by the mottled sculpin,
plotted as a function of source distance. The detectability of
the source ($p(A)$), which decreases with source distance, fell
below chance levels ($p(A) < 0.76$ plotted as a function of source distance. The detectability of
the source ($p(A)$), which decreases with source distance, fell
below chance levels ($p(A) < 0.76$) at a distance of *ca*. 11 cm,
regardless of which behavioural the source $(p(A))$, which decreases with source distance, fell
below chance levels $(p(A) < 0.76)$ at a distance of *ca*. 11 cm,
regardless of which behavioural measure was used (pooled
data from four animals) (b). The effect regardless of which behavioural measure was used (pooled data from four animals). (b) The effect of CoCl₂ on the regardless of which behavioural measure was used (pooled
data from four animals). (b) The effect of $CoCl_2$ on the
frequency of untrained approaches to a dipole source in four
individual sculpin. Prior to pharmacological i data from four animals). (*b*) The effect of CoCl₂ on the
frequency of untrained approaches to a dipole source in four
individual sculpin. Prior to pharmacological inactivation,
nearly all presentations of a vibrating b frequency of untrained approaches to a dipole source in four
individual sculpin. Prior to pharmacological inactivation,
nearly all presentations of a vibrating bead caused the fishes
to approach to source. After CoCl, trea individual sculpin. Prior to pharmacological inactivation,
nearly all presentations of a vibrating bead caused the fishes
to approach to source. After CoCl₂ treatment, approaches to
the source were nearly abolished (c). mearly all presentations of a vibrating bead caused the fishes
to approach to source. After $CoCl₂$ treatment, approaches to
the source were nearly abolished. (*c*) The effect of $CoCl₂$ on
source detectability as to approach to source. After $CoCl₂$ treatment, approaches to
the source were nearly abolished. (c) The effect of $CoCl₂$ on
source detectability as measured with conditioned suppression
of respiration. $CoCl₂$ the source were nearly abolished. (c) The effect of CoCl₂ on
source detectability as measured with conditioned suppression
of respiration. CoCl₂ inactivation had no substantial effect on
this animal's performance ind source detectability as measured with conditioned suppression
of respiration. $CoCl_2$ inactivation had no substantial effect on
this animal's performance, indicating that its behaviour may
be completely explained with refe of respiration. CoCl₂ inactivation had no substantial effect on
this animal's performance, indicating that its behaviour may
be completely explained with reference to the inner ear alone
(functions from the responses of this animal's performance, indicating that its behaviour may
be completely explained with reference to the inner ear alone
(functions from the responses of a single animal before and
after treatment) (functions from the responses of a single animal before and after treatment).

paradigm, animals were conditioned to suppress respiration paradigm, animals were conditioned to suppress respiration
when they detected the source by repeated pairing of the source
and a small electric shack We measured prepiration before and paradigm, animals were conditioned to suppress respiration
when they detected the source by repeated pairing of the source
and a small electric shock. We measured respiration before and
during the stimulus presentation to and a small electric shock. We measured respiration before and during the stimulus presentation to calculate a suppression ratio.

BIOLOGICAL
SCIENCES

THE ROYAL
SOCIETY

**PHILOSOPHICAL
TRANSACTIONS
TRANSACTIONS**

Both behavioural measures, suppression ratios and changes in Both behavioural measures, suppression ratios and changes in
angular relations to the source were compared during signal and
non-signal trials according to the tenets of signal detection Both behavioural measures, suppression ratios and changes in
angular relations to the source were compared during signal and
non-signal trials according to the tenets of signal detection
theory by calculating receiver oper non-signal trials according to the tenets of signal detection
theory by calculating receiver operating characteristic (ROC) non-signal trials according to the tenets of signal detection
theory by calculating receiver operating characteristic (ROC)
curves. The area underneath the ROC curve, $p(A)$, is a measure of
detectability and is plotted as theory by calculating receiver operating characteristic (ROC)
curves. The area underneath the ROC curve, $p(A)$, is a measure of
detectability and is plotted as a function of distance for both
hebavioural measures in figur curves. The area underneath the ROC curve, $p(A)$, is a measure of detectability and is plotted as a function of distance for both behavioural measures in figure 2. $p(A)$ is a measure of the separation between the distribu detectability and is plotted as a function of distance for both
behavioural measures in figure 2. $p(A)$ is a measure of the separa-
tion between the distribution of responses recorded when a signal
is present and when it behavioural measures in figure 2. $p(A)$ is a measure of the separation between the distribution of responses recorded when a signal
is present and when it is absent. A $p(A)$ -value of 0.5 indicates
completely overlapping d tion between the distribution of responses recorded when a signal
is present and when it is absent. A $p(A)$ -value of 0.5 indicates
completely overlapping distributions and a $p(A)$ -value of 0.76
indicates a separation betw completely overlapping distributions and a $p(A)$ -value of 0.76 indicates a separation between the means of the distributions of one full standard deviation and is typically used as a threshold indicates a separation between the means of the distributions of
one full standard deviation and is typically used as a threshold
response. For a complete discussion of ROC curves, see
Gescheider (1997) one full standard de
response. For a c
Gescheider (1997).

Gescheider (1997).
To determine the sensory substrates of our behavioural Gescheider (1997).

To determine the sensory substrates of our behavioural

measures, we used $CoCl_2$ to inactivate the lateral line system.

Overnight immersion in $O~lmM$ CoCl, inactivates the lateral To determine the sensory substrates of our behavioural
measures, we used $CoCl_2$ to inactivate the lateral line system.
Overnight immersion in $0.1 \text{mM } CoCl_2$ inactivates the lateral
line for un to two works but has no eff measures, we used $CoCl_2$ to inactivate the lateral line system.
Overnight immersion in 0.1mM CoCl_2 inactivates the lateral
line for up to two weeks, but has no effect on the inner ear hair
cells (Karlsen & Sand 1987) W line for up to two weeks, but has no effect on the inner ear hair cells (Karlsen & Sand 1987). We compared the frequency of approaches to a nearby ($<$ 5 cm) source before and after $CoCl_2$ treatment to determine the role of the lateral line system in approaches to a nearby $(< 5 \text{ cm})$ source before and after $CoCl₂$ approaches to a nearby ($\lt 5$ cm) source before and after CoCl₂
treatment to determine the role of the lateral line system in
unconditioned orientating responses. We also examined the
officet of CoCl₂ treatment on de treatment to determine the role of the lateral line system in
unconditioned orientating responses. We also examined the
effect of CoCl₂ treatment on detection of the source as assessed
by conditioned suppression of respi effect of $CoCl₂$ treatment on detection of the source as assessed by conditioned suppression of respiration.

3. THE DISTANCE RANGE OF DIPOLE SOURCE : DISTANCE RANGE OF DIPOLE SOURC
DETECTION IN MOTTLED SCULPIN

DETECTION IN MOTTLED SCULPIN
The psychometric functions for both behavioural measures (¢gure 2*a*) are quite similar. In both behavioural approaches, the threshold distance is approximeasures (figure 2*a*) are quite similar. In both behavioural approaches, the threshold distance is approximately 11cm. The fishes used in these experiments ranged from $7-10 \text{ cm}$ standard length (SL) so the range vioural approaches, the threshold distance is approximately 11 cm. The fishes used in these experiments ranged from 7–10 cm standard length (SL), so the range of dinole detection is ca 1–1.5 body lengths While both mately 11 cm. The fishes used in these experiments
ranged from 7–10 cm standard length (SL), so the range
of dipole detection is ca . 1–1.5 body lengths. While both
hehavioural measures gave very similar estimates of the ranged from 7–10 cm standard length (SL), so the range
of dipole detection is ca . 1–1.5 body lengths. While both
behavioural measures gave very similar estimates of the of dipole detection is *ca*. 1–1.5 body lengths. While both
behavioural measures gave very similar estimates of the
distance range of source detection, each behavioural
measure apparently relies on a different sensory moda behavioural measures gave very similar estimates of the distance range of source detection, each behavioural measure apparently relies on a different sensory modality.
CoCl., treatment, nearly eliminated the unconditioned distance range of source detection, each behavioural
measure apparently relies on a different sensory modality.
CoCl₂ treatment nearly eliminated the unconditioned
orientating responses to the source (figure $2b$) but measure apparently relies on a different sensory modality.
CoCl₂ treatment nearly eliminated the unconditioned
orientating responses to the source (figure 2*b*), but
annears to have had no effect on the behavioural $CoCl₂$ treatment nearly eliminated the unconditioned
orientating responses to the source (figure 2b), but
appears to have had no effect on the behavioural
performance in the conditioning paradigm (preliminary orientating responses to the source (figure $2b$), but appears to have had no effect on the behavioural performance in the conditioning paradigm (preliminary appears to have had no effect on the behavioural
performance in the conditioning paradigm (preliminary
data are shown in figure $2c$). Orientating responses
therefore depend on lateral line information but condiperformance in the conditioning paradigm (preliminary
data are shown in figure $2c$). Orientating responses
therefore depend on lateral line information but condi-
tioned responses may be explained by use of the inner ear data are shown in figure $2c$). Orientating responses therefore depend on lateral line information but conditioned responses may be explained by use of the inner ear alone alone. tioned responses may be explained by use of the inner ear alone.
Surprisingly then, both the inner ear and the lateral

alone.

Surprisingly then, both the inner ear and the lateral

line system may have very similar operating ranges in the

mottled sculpin. How can we explain the similarity in Surprisingly then, both the inner ear and the lateral
line system may have very similar operating ranges in the
mottled sculpin. How can we explain the similarity in
distance range for these two systems? The most obvious line system may have very similar operating ranges in the
mottled sculpin. How can we explain the similarity in
distance range for these two systems? The most obvious
explanation lies in the fact that mottled sculpin are mottled sculpin. How can we explain the similarity in distance range for these two systems? The most obvious explanation lies in the fact that mottled sculpin are distance range for these two systems? The most obvious
explanation lies in the fact that mottled sculpin are
benthic fishes. These fishes are generally denser than the
surrounding water, decreasing the acceleration imposed explanation lies in the fact that mottled sculpin are
benthic fishes. These fishes are generally denser than the
surrounding water, decreasing the acceleration imposed
on the fishes by any given pressure gradient. In addit benthic fishes. These fishes are generally denser than the surrounding water, decreasing the acceleration imposed
on the fishes by any given pressure gradient. In addition,
friction, coupling, between, the fishes, and, the surrounding water, decreasing the acceleration imposed
on the fishes by any given pressure gradient. In addition,
friction coupling between the fishes and the substrate on the fishes by any given pressure gradient. In addition, friction coupling between the fishes and the substrate would also act to reduce the acceleration of the fishes. While this has never been explicitly explored, it i friction coupling between the fishes and the substrate
would also act to reduce the acceleration of the fishes.
While this has never been explicitly explored, it is also
possible that benthic animals might have active post would also act to reduce the acceleration of the fishes.
While this has never been explicitly explored, it is also
possible that benthic animals might have active postural
control systems that act to limit their motions in While this has never been explicitly explored, it is also
possible that benthic animals might have active postural
control systems that act to limit their motions in response
to accelerations of the surrounding water (perh possible that benthic animals might have active postural
control systems that act to limit their motions in response
to accelerations of the surrounding water (perhaps simply
as a means of producing negative lift to keep t control systems that act to limit their motions in response
to accelerations of the surrounding water (perhaps simply
as a means of producing negative lift to keep the fishes on
the substrate). All of these factors contrib to accelerations of the surrounding water (perhaps simply
as a means of producing negative lift to keep the fishes on
the substrate). All of these factors contribute to a decrease
in the relative effectiveness of a stimulu as a means of producing negative lift to keep the fishes on
the substrate). All of these factors contribute to a decrease
in the relative effectiveness of a stimulus to the inner ear,
but would have an opposite effect on t the substrate). All of these factors contribute to a decrease
in the relative effectiveness of a stimulus to the inner ear,
but would have an opposite effect on the lateral line.

On the contrary, reduction of fish motion may actually On the contrary, reduction of fish motion may actually
act to increase the distance range of the lateral line. As
described above fish motion effectively reduces the On the contrary, reduction of fish motion may actually
act to increase the distance range of the lateral line. As
described above, fish motion effectively reduces the
intensity and alters the spatial pattern of lateral lin described above, fish motion effectively reduces the
intensity and alters the spatial pattern of lateral line described above, fish motion effectively reduces the
intensity and alters the spatial pattern of lateral line
stimulation, particularly in the outer reaches of the near
field (Kalmiin 1989) If the fish is held rigidly due intensity and alters the spatial pattern of lateral line
stimulation, particularly in the outer reaches of the near
field (Kalmijn 1989). If the fish is held rigidly due to
friction with the substrate or active postural co stimulation, particularly in the outer reaches of the near
field (Kalmijn 1989). If the fish is held rigidly due to
friction with the substrate or active postural control
mechanisms, the pattern and intensity of stimulatio field (Kalmijn 1989). If the fish is held rigidly due to friction with the substrate or active postural control mechanisms, the pattern and intensity of stimulation of the lateral line may be closer to the conditions of th friction with the substrate or active postural control
mechanisms, the pattern and intensity of stimulation of
the lateral line may be closer to the conditions of the
stimulus field itself. The same factors that act to dec mechanisms, the pattern and intensity of stimulation of
the lateral line may be closer to the conditions of the
stimulus field itself. The same factors that act to decrease
inner ear stimulation would thus also act to incr the lateral line may be closer to the conditions of the stimulus field itself. The same factors that act to decrease inner ear stimulation would thus also act to increase lateral line stimulation stimulus field itself. The :
inner ear stimulation w
lateral line stimulation.

4. FUTURE DIRECTIONS

The studies described above suggest several fruitful **4. FOTOKE DIRECTIONS**
The studies described above suggest several fruitful
avenues for ongoing research. For example, what is the
actual range of fish motion in response to vibratory The studies described above suggest several fruitful
avenues for ongoing research. For example, what is the
actual range of fish motion in response to vibratory
sources? How does imposed fish motion depend on the avenues for ongoing research. For example, what is the
actual range of fish motion in response to vibratory
sources? How does imposed fish motion depend on the
habitat and morphology of the fish and do active actual range of fish motion in response to vibratory
sources? How does imposed fish motion depend on the
habitat and morphology of the fish, and do active
postural control mechanisms exist that limit or enhance sources? How does imposed fish motion depend on the habitat and morphology of the fish, and do active postural control mechanisms exist that limit or enhance fish motion? Furthermore, do midwater fishes actually habitat and morphology of the fish, and do active postural control mechanisms exist that limit or enhance
fish motion? Furthermore, do midwater fishes actually
have a reduced lateral line distance range relative to
benthic fishes? Conversely do midwater fishes have an fish motion? Furthermore, do midwater fishes actually
have a reduced lateral line distance range relative to
benthic fishes? Conversely, do midwater fishes have an
enlarged inner ear active space? have a reduced lateral line dista
benthic fishes? Conversely, do mi
enlarged inner ear active space?
Empirical determination of the benthic fishes? Conversely, do midwater fishes have an enlarged inner ear active space?
Empirical determination of the spatial resolving power

enlarged inner ear active space?
Empirical determination of the spatial resolving power
and localizing abilities of both the lateral line and
otolithic endorgans is desperately needed. Currently we Empirical determination of the spatial resolving power
and localizing abilities of both the lateral line and
otolithic endorgans is desperately needed. Currently we
are investigating the difference in spatial resolution of and localizing abilities of both the lateral line and
otolithic endorgans is desperately needed. Currently we
are investigating the difference in spatial resolution of
dinole sources in intact and lateral-line-impaired scu otolithic endorgans is desperately needed. Currently we
are investigating the difference in spatial resolution of
dipole sources in intact and lateral-line-impaired sculpin.
We predict that spatial discrimination will be s are investigating the difference in spatial resolution of dipole sources in intact and lateral-line-impaired sculpin.
We predict that spatial discrimination will be severely
reduced in lateral-line-inactivated sculpin. For midwater
fishes, if there is a larger difference in the d reduced in lateral-line-inactivated sculpin. For midwater reduced in lateral-line-inactivated sculpin. For midwater
fishes, if there is a larger difference in the distance range
of the inner ear and lateral line system, there should also
be a reduction in spatial resolving power fishes, if there is a larger difference in the distance range
of the inner ear and lateral line system, there should also
be a reduction in spatial resolving power in the inter-
mediate range where inertial audition is sti of the inner ear and lateral line system, there should also
be a reduction in spatial resolving power in the inter-
mediate range, where inertial audition is still effective but
the lateral line is not be a reduction in spatial resolving power in the inter-
mediate range, where inertial audition is still effective but
the lateral line is not.

While controversies over the nature of the stimulus the lateral line is not.
While controversies over the nature of the stimulus
(note the diversity of views expressed in the chapters and
discussions contained in Cahn (1967)) no longer plague While controversies over the nature of the stimulus
(note the diversity of views expressed in the chapters and
discussions contained in Cahn (1967)) no longer plague
the field of acousticolateralis research the biological discussions contained in Cahn (1967)) no longer plague
the field of acousticolateralis research, the biological role discussions contained in Cahn (1967)) no longer plague
the field of acousticolateralis research, the biological role
and actual sensory capabilities of inertial audition and the
lateral line system are still in dire need o the field of acousticolateralis research, the biological role
and actual sensory capabilities of inertial audition and the
lateral line system are still in dire need of empirical
research. The elegant behavioural experimen and actual sensory capabilities of inertial audition and the
lateral line system are still in dire need of empirical
research. The elegant behavioural experiments of
Diikaraaf (1963) and theoretical treatments of Kalmiin lateral line system are still in dire need of empirical
research. The elegant behavioural experiments of
Dijkgraaf (1963) and theoretical treatments of Kalmijn research. The elegant behavioural experiments of Dijkgraaf (1963) and theoretical treatments of Kalmijn (1988, 1989) have effectively argued for the importance of spatial gradients of water motion as the stimulus to the Dijkgraaf (1963) and theoretical treatments of Kalmijn (1988, 1989) have effectively argued for the importance of spatial gradients of water motion as the stimulus to the auditory and bydrodynamic senses but few relevant (1988, 1989) have effectively argued for the importance of spatial gradients of water motion as the stimulus to the auditory and hydrodynamic senses, but few relevant experimental data, have been collected Behavioural spatial gradients of water motion as the stimulus to the auditory and hydrodynamic senses, but few relevant experimental data have been collected. Behavioural responses to relevant stimuli, such as a near field dipole experimental data have been collected. Behavioural experimental data have been collected. Behavioural responses to relevant stimuli, such as a near field dipole source, are the best means of determining the hydro-
dynamic sensory capabilities of aquatic organisms responses to relevant stimuli, such as a near field of source, are the best means of determining the h
dynamic sensory capabilities of aquatic organisms.

dynamic sensory capabilities of aquatic organisms.
We are extremely grateful to Dr S. Collin and Dr J. Marshall for
the opportunity to participate in this conference. We also thank We are extremely grateful to Dr S. Collin and Dr J. Marshall for
the opportunity to participate in this conference. We also thank
the faculty and staff of Parmly Hearing Institute for financial We are extremely grateful to Dr S. Collin and Dr J. Marshall for
the opportunity to participate in this conference. We also thank
the faculty and staff of Parmly Hearing Institute for financial
and intellectual support. Th the opportunity to participate in this conference. We also thank
the faculty and staff of Parmly Hearing Institute for financial
and intellectual support. The research described in this paper is
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Neurosci. Abst. (In the press.)
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- lateral line organs. *Biol. Rev.* **38**, 51–105.

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particle motion in three dimensions. *Science* 225, 951–954.

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- particle motion in three dimensions.

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