Headphone amplifier output resistance … an explanation

Impedances and resistances are not the same but are closely related.
A **resistance** is a constant value that does not alter with various frequencies or power and the current flowing through a resistance has a linear correlation to the voltage across the resistor.
An **impedance** is a varying resistance which is different in resistance value for various frequencies and thus the current does NOT have a linear correlation to the applied voltage.
The current may even have a different phase relation to that of the applied voltage.

Headphones are specified to have a certain 'Ohmic' value.
This is usually the DC resistance of the voicecoil in the driver and is (in most cases) also is equal to the impedance around 1kHz too and is mentioned in Ohms(Ω) as a resistance.
Loudspeakers are usually specified to have impedances of 4, 6 or 8 Ω but can have impedances varying between 1 Ω and 100 Ω. This is mainly caused by badly configured crossover filters in loudspeakers which headphones do not have.
For headphones the impedance can only be higher then the Ohmic value which normally is given in the specifications.
Ortho-dynamic headphones usually have a linear resistance and this has to do with their construction and are not discussed specifically. Electrostatic speakers with transformers and 'normal' cone type headphones have impedances.

In short: Headphones and loudspeakers have impedances (i.e. varying resistances dependent of the frequency).
Amplifiers have constant output resistances (within the audible range)

Headphone amplifiers all have a certain output resistance which is NOT specified in most cases.
Only the range of headphones that can be used is mentioned , for instance 16 - 600 Ω or 32 - 600 Ω or 16 Ω - 64 Ω.

The output resistance DOES influence the sound of the used headphone, in some cases more then others.
Cause of all this is the varying impedance of a headphone in relation to the fixed resistance of an amplifier.
This is discussed on page 3.

Why are there output resistors in the first place ?
They are there to protect the headphones from too much current and thus too much power which could destroy certain (low Ohmic) headphones.

How can headphones be destroyed by headphone amplifiers ?
Headphone drivers have extremely thin wires because they need to be extremely light to reach the highest frequencies without any problems.
More weight (= thicker copper wires) adds weight to the diaphragm, which must be as light as possible.
Thin wires means they cannot carry much current .
They will glow like a light bulb and burn out or get loose from the material they are wound upon causing the drivers to distort or fail.

Most dynamic headphones (not ortho-dynamic type) are specified to have a power handling capacity of around 100mW to 200mW regardless of their impedance.
They can handle short peak values that are much higher but not continuously.
Above the specified powers most headphones do not react linear anymore meaning the excursions of the diaphragm do not follow the applied electrical signal anymore but are smaller then 'expected'.
A form of soft-clipping.

Since audio amplifiers provide an output VOLTAGE and have a theoretical output resistance of 0Ω (a few tens of mΩ in practice) and headphones have different impedances this would result in hugely different power levels.
High Ohmic headphones will not have much current running through them at the maximum output voltage of an amplifier.
Low Ohmic headphones, however, will have (too) much current flowing through them at the maximum output voltage of the same amplifier **IF** there were no output resistors.

An example:
10V output voltage on a 300 Ω **(high Ohmic)** headphone will result in a current of 10 V/300 Ω = 33.3mA.
The output power can be calculated as: 10 V x 33.3 mA = 330 mW.
This is already above the 100 mW to 200 mW level but when music is applied only short peaks will reach these values and the average levels will be MUCH lower so no real danger to 300 Ω (and higher) headphones.
10 V voltage with a 32 Ω **(low Ohmic)** headphone will result in a current of 10 V/32 Ω = 312mA
10V x 312mA = 3,125 mW (3.125W !)
These levels will certainly burn out the coils of this headphone as they can only take about 200 mW (0.2 W) max !

The output resistors in headphone amplifiers LIMIT the currents that can flow which are determined by the maximum output voltage of the amplifier and the resistance (impedance) that forms the load of the amplifier.

When a resistor is in series with the impedance of the headphone the current is limited as I (current) = U (voltage) divided by the total (output resistance + headphone impedance) resistance (R)

The same amplifier as mentioned on the previous page with a 120 Ω output resistance in it's output will result in the following output powers.

High Ohmic: 10 V/(120 Ω + 300 Ω) = 24 mA.
Because of the voltage division that occurs because the output resistance and headphone impedance are in series the voltage on the headphone is no longer 10V but only a certain percentage of it.
The voltage devision that takes place follows an easy rule.
The voltage across the load (headphone) can be calculated as $U_{hp} = U_{out} \times R_{hp}/(R_{hp}+R_{amp})$
Since U(voltage in Volt) =I(current in Amps) x R(Resistance in Ω) and P (power in Watt) = U(Volt) x I(Amps) the power can also be calculated with the equation: $I^2 \times R$
The calculated output power in this case will be: $(24\text{ mA})^2 \times 300\ \Omega$ = 173 mW which cannot destroy high-Ohmic headphones.

Low Ohmic: 10 V/(120 Ω + 32 Ω) = 66 mA.
Because of the voltage division the power can be calculated by: $I^2 \times R$ so $66\text{ mA}^2 \times 32$ = 139 mW which cannot destroy low Ohmic headphones.

In this example it is clearly shown that when an amplifier is fitted with a certain output resistor all types of headphones receive about the same maximum output POWER and headphones will not receive powers (far) beyond their maximum ratings which could destroy the delicate voice coils.

Why was a 120 Ω used in the example ?
This value has been adopted by most headphone manufacturers as a standard value.
The sound (in most cases) of these headphones has been 'tailored' to sound correctly (as intended) when this value is used.

Not all manufacturers do use this standard and only a few manufacturers mention this resistance.
It is obvious why as this explanatory article is already getting lengthy and I am not even halfway in explaining.
So they do not mention anything about it because most users do not understand nor are interested in this.

Why are some amplifier resistances lower in value ?
This has to do with the maximum output voltage that the amp can deliver (without a load).
The output voltage (Volt) that an amplifier can deliver is dependent on the power supply voltage and output stage configuration.
Roughly the output voltage in V_{RMS} (Root Mean Square) is about 1/3 of the total power supply voltage.
So an amplifier with 1 single 9V battery can deliver about $3V_{RMS}$
An amplifier with a single voltage of 24V can deliver $8V_{RMS}$
A dual voltage supply rails of +15V and -15V (total 30V) can deliver $10V_{RMS}$.
An MP3 player (or other battery operated device) with 2 (rechargeable) AA batteries for instance only has 2.4V available so can only deliver 0.8V provided they don't use an internal DC/DC voltage converter (booster) to create a higher voltage.

It is obvious different amps can have different output voltages.
IF the maximum voltage is not high it will not be able to deliver enough power into high-Ohmic headphones but can deliver reasonable amounts of power in Low Ohmic headphones as these don't need much voltage to reach the needed currents (= power) provided the output resistors are lower in value then 120 Ω.
These low voltage amplifiers therefor don't need current limiting resistors in the output path.

In short: High voltage amps can drive high and low Ohmic headphones with a series resistor, low voltage amps can only drive low Ohmic headphones and do not need output resistors.
In practice they have them but only a few Ohms (between 10 mΩ and 10 Ω in general)

Amplifiers with a medium output voltage therefor often have a resistance between 0 Ω and 120 Ω (maybe 30 Ω, 47 Ω or 56 Ω) so they can drive low Ohmic headphones to their maximum value and higher Ohmic headphones pretty well but NOT to their maximum power but still to very acceptable levels.

These 2 pages all have been about explaining why and what resistors are used for in headphone amplifiers and it is shown that is has nothing to do with impedance matching as is often stated.
Impedance matching is only needed for very high frequency signal transfer (FAR beyond the audible range and above 1MHz) with cables that need to have a similar impedance as the in and output resistances of the source and receiving end.
This is NOT needed nor applicable in the entire audio range, even up to 50kHz.

In short:

1: The output impedance does NOT have to match the impedance of the headphone NOR is this desirable.
2: Output resistors are only needed to limit output currents to protect headphones when amps can deliver higher voltages.
3: These resistor values are dependent of the range of suitable headphones and maximum output voltage.

Why are there many different headphone impedances ?

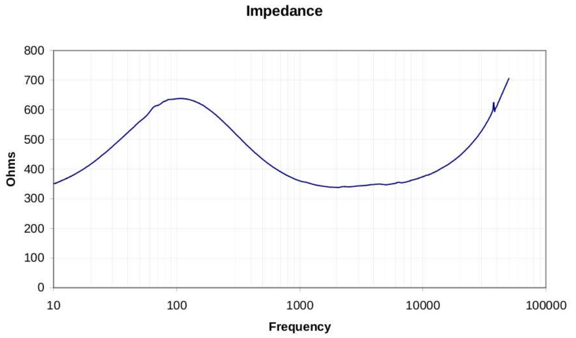
This has to do with the intended usage. Low Ohmic headphones are designed to be used with portable equipment which does not have a large output voltage swing. High Ohmic headphones are designed to be used with higher voltage amplifiers. Some headphones can be purchased (for above mentioned reasons) in different impedances. The different output resistances of the used output amps for these editions have their sonic effect and also the weight difference of the different voicecoils have influence on the sound.

Is the sound affected by different output resistances ?

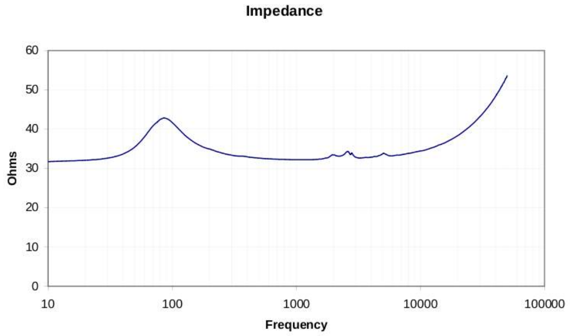
The answer is yes, but how much the sound is affected depends on the value of the output resistors in the amps, the impedance of the headphone and how much this impedance varies with different frequencies.
Also an important ingredient is IF the headphone is optimized to perform as it should with a certain output resistance or if this was not included in the design.
Some headphones are designed to have the sought after frequency response when this specific output resistance is used.
A normalized value is 120 Ω for most modern designs though it is rarely mentioned in the specifications sheet of the headphone itself.
It DOES, however, influence the sound.

HOW does the impedance of a headphone influence the sound ?
Actually it is the other way around.
The impedance for low frequencies is mostly determined by mechanical properties of the driver.
Everything in nature wants to vibrate on their preferred frequency or multiple frequencies.
When this resonance point is neared or reached there is less power needed to get the same excursions as would otherwise be needed as the driver also acts as a generator at this point and generates a 'counter voltage'.
Less power is needed when the same voltage is applied and this can only result in less current drawn.
Less current with the same voltage means the resistance has to be higher.
So at lower frequencies (the resonance point of speakers and headphones) the impedance rises.
The same thing happens at higher frequencies if the driver has certain resonance points.
These can be seen as little peaks in the impedance graph and means the driver resonates at this frequency which is NEVER a good thing but does not need to sound awful either.

Here are a few graphs that are typical.



HD800 (high-Ohmic, 350 Ω nominal)

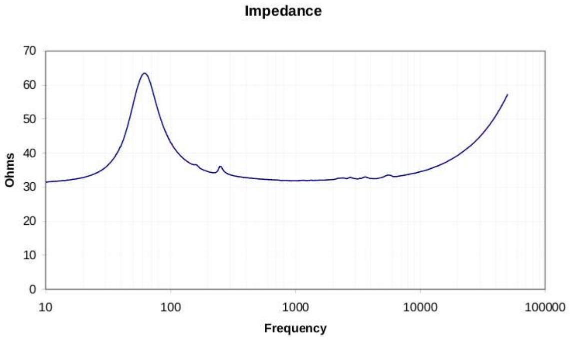


Grado SR60 (low-Ohmic, 32 Ω nominal)

What can be observed is the (wide) hump in the 100Hz region of the Sennheiser HD800 which almost doubles in impedance around that frequency to well above 600 Ω. There are little resonances seen in this graph. The impedance rises again the higher the frequencies go from 10kHz and up. At 20kHz the impedance is already 450 Ω.

The Grado is Low Ohmic and the hump in the lows is less wide and reaches about 42 Ω around 90 Hz. A few resonances can be seen between 2kHz and 3kHz and at 6kHz. From 10kHz the impedance starts to rise again. At 20kHz it is around 35 Ω.
There are also low-Ohmic headphones with higher impedance peaks around 100 Hz and high Ohmic headphones with lower humps. This varies between headphones, as can be seen in the graph of the Rudistore Chroma on the right.

The rising of the impedance above 10kHz is not due to resonances but is caused by the inductance of the voicecoil that starts to play a role as well as the mechanical properties of the membrane.



Rudistore Chroma (low-Ohmic, 32 Ω nominal)

Orthodynamic (planar) headphones usually have an impedance characteristic that looks like a straight line due to their construction and is beside the obvious drop in SPL not affected in the frequency domain.

What are the sonic consequences ?

As can be seen on the graphs of the previous page the impedance varies quite a lot in some cases and less in other. The HD800 and Rudistore rise about 100% in impedance around 100Hz for the HD800 and 80Hz (Chroma) while the Grado only rises about 50% around 90 Hz. The bandwidth of this peak also is different but all exhibit this behavior in the low region (bass). The frequencies above 10kHz climb only slightly.

As is explained above the output resistance of an amplifier is constant and the impedance of the headphones varies but does so dependent of the headphone type.
On the top part of page 2 there is an explanation as to how the output voltage is divided because the output resistance (which is constant) has a relation to the load (headphone) impedance in series with the output resistor.
Since this impedance varies the voltage across the headphone varies too.
HOW much and which frequencies are affected is determined by the impedance characteristic of the headphone itself with respect to the output resistance of the amplifier.
If there was NO output resistance present in the amplifier the impedance characteristic would have NO influence at all on the sound (the frequency response).
The higher this output resistance the more dramatic the effect depending on the characteristic of the headphone in question.

The voltage across the headphone determines how loud that frequency is reproduced.
This voltage can be calculated.
U_{out} = HP resistance / (output resistance+HP resistance) at a specific frequency.
U_{out} is normalised and then converted to dB for comparative reasons.

As an example the Grado SR60:

with 10 Ω output resistance: The output voltage around 1 kHz, U_{out} = 32/(10+32) = 0.762 = - 2.3 dB
with 10 Ω output resistance: The output voltage around 90 Hz, U_{out} = 43/(10+43) = 0.811 = - 1.8 dB
with 10 Ω output resistance: The output voltage around 20 kHz, U_{out} = 35/(10+35) = 0.777 = - 2.2 dB

When one considers 1 kHz as 0 dB reference it is evident that 90 Hz is boosted by 0.5 dB and 20kHz 0.1 dB which is virtually unnoticeable.

with 120 Ω output resistance: The output voltage around 1 kHz, U_{out} = 32/(120+32) = 0.21 = - 13.5 dB
with 120 Ω output resistance: The output voltage around 90 Hz, U_{out} = 43/(120+43) = 0.26 = - 11.6 dB
with 120 Ω output resistance: The output voltage around 20 kHz, U_{out} = 35/(120+35) = 0.225 = - 12.9 dB

Again when one considers 1 kHz as 0 dB the 90 Hz is boosted 1.9 dB and 20kHz 0.6 dB which is noticeable in the lows only and a very small portion of it directly around 90Hz.
Bass reproduction on a 120 Ω output resistance amplifier will thus be 1.4 dB more which is just noticeable in AB comparisons. The 0.5 dB increase at 20kHz will go unnoticed by many.

The Rudistore Chroma shows a different dependency of the output resistance:

with 10 Ω output resistance: The output voltage around 1 kHz, U_{out} = 32/(10+32) = 0.762 = - 2.3 dB
with 10 Ω output resistance: The output voltage around 70 Hz, U_{out} = 62/(10+62) = 0.86 = - 1.3 dB
with 10 Ω output resistance: The output voltage around 20 kHz, U_{out} = 40/(10+40) = 0.8 = - 1.9 dB

When one considers 1 kHz as 0 dB it is clear that 70 Hz is boosted 1 dB and 20kHz 0.4 dB.

with 120 Ω output resistance: The output voltage around 1 kHz, U_{out} = 32/(120+32) = 0.21 = - 13.5 dB
with 120 Ω output resistance: The output voltage around 70 Hz, U_{out} = 62/(120+62) = 0.34 = - 9.4 dB
with 120 Ω output resistance: The output voltage around 20 kHz, U_{out} = 40/(120+40) = 0.25 = - 12.0 dB

Again when one considers 1 kHz as 0 dB the 70 Hz is boosted by 4.1 dB and 20kHz by 1.5 dB which is quite noticeable in the lows.
Bass reproduction on a 120 Ω output resistance amplifier will thus be 3.1 dB higher which is clearly noticeable in AB comparisons. The 1 dB increase at 20kHz will go almost unnoticed but can be detected by trained ears.

Both these headphones are 32 Ω nominal but do have different sonic differences between high and low Ohmic amplifiers.

For the Sennheiser HD800 it's a similar story but because the impedance peak is MUCH wider not only a specific part of the lows are 'boosted' with a high-Ohmic amplifier but also everything down to 40 Hz and upto 300 Hz.
Calculations for the HD800 are on the next page.

The Sennheiser HD800 dependency of the output resistance of amplifiers:

with 10 Ω output resistance: The output voltage around 1 kHz, U_{out} = 350/(10+350) = 0.97 = - 0.24 dB
with 10 Ω output resistance: The output voltage around 100 Hz, U_{out} = 630/(10+630) = 0.98 = - 0.14 dB
with 10 Ω output resistance: The output voltage around 20 kHz, U_{out} = 450/(10+450) = 0.98 = - 0.19 dB

When one considers 1 kHz as 0 dB 100 Hz is boosted 0.1 dB and 20kHz 0.05 dB.
As flat as can be.

with 120 Ω output resistance: The output voltage around 1 kHz, U_{out} = 350/(120+350) = 0.74 = - 2.56 dB
with 120 Ω output resistance: The output voltage around 100 Hz, U_{out} = 630/(120+630) = 0.84 = - 1.5 dB
with 120 Ω output resistance: The output voltage around 20 kHz, U_{out} = 450/(120+450) = 0.79 = - 2.05 dB

Again when one considers 1 kHz as 0 dB it is evident that 100 Hz is boosted 1 dB and 20kHz 0.5 dB which is barely noticeable in the lows but could be picked out when doing an AB comparison.
Bass reproduction on a 120 Ω output resistance amplifier will thus be 0.9 dB more which is noticeable in AB comparisons.
The 0.4 dB increase at 20kHz will go almost unnoticed but can be detected by some.

The Sennheiser HD650 and HD600 show somewhat similar behavior but less prominent (smaller differences).
These headphones will therefor give slightly more 'warmth' and 'body' when played through a higher impedance.

Headphones that have a 'bathtub' frequency graph (boosted highs and lows) might benefit from a low output impedance amplifier because the bass will be reproduced slightly lower in level which will make the bass sound tighter which isn't a bad thing for this headphone.

The AKG K701 will not very much in the lows like the sennheisers do as the impedance hardly rises in the lows (very well damped) and only increases in the highs and sooner then most headphones.
This is caused by the inductance of the voicecoil and therefore the highs will alter more and become slightly more refined and less aggressive without a decrease of 'details'.

What about the damping factor ?

The damping factor is the load resistance devided by the output resistance (R_{load} / R_{out}) and is because of the used output resistors not of much importance and does not damp much either.
This is because the load impedance is high compared to the output resistance of the amplifier meaning a current that is generated by the driver (it acts as a microphone for its own movement) is determined by the resistance of the voicecoil + output resistance. The biggest part in high-Ohmic headphones is the driver and thus has very little to no influence.
Low Ohmic headphones can have somewhat more damping from low output resistance amplifiers as the impedance of the voice coil is lower then the output resistance of high-Ohmic output resistances of the amplifier. But even with an output resistance of 10 Ω the damping of a low-Ohmic driver is still negligible.
It's not such a major problem in headphones as it is with loudspeakers.

In short:

Besides the obvious drop in total sound pressure levels (see page 4), some headphones will also give a different sound signature (frequency response) when used on amplifiers with different impedances even if otherwise similar.
Mostly in the bass department which can 'mask' higher frequencies and thus seem to affect the mids and highs too.
All dependent of the output resistance of the amplifier and impedance characteristics of headphone in question.

The output resistors are there to protect low-Ohmic headphones from blowing up when driven from an amplifier that has higher output voltages (10V to 12V) so be careful when installing low-ohmic output resistors in higher voltage amplifiers such as the Panda and SCHA when using low-ohmic headphones.
High-Ohmic headphones don't need this protection but low-Ohmic headphones do and that's what they are there for to protect and to make sure there are no big jumps in SPL (sound Pressure Level) when switching from high- to low-Ohmic headphones as the average power levels (and thus SPL with similar dB/mW sensitivity) will be more equal.

The lower the maximum output voltage of the amplifier is, the lower this resistor can be.
Low voltage amplifiers (battery operated) don't need, and usually don't have, higher output resistances but cannot drive high-ohmic headphones as loud as low Ohmic.

Battery operated DAP's have very low output voltages and low output resistances as well and can only drive high efficiency low-Ohmic headphones well (not K701 as it's not high efficiency).
Most of these players will benefit from an added portable amp for these reasons alone (there are more reasons).

When one considers most headphones are designed to perform at their best with a 120 Ω output resistance it is obvious that low Ohmic output resistances of amplifiers can make the bass appear to be 'thinner' and also affect the highs a bit.
This might be a good thing for some cans and become less attractive for other headphones.